CALIFORNIA ENERGY
COMMISSION

Final Report Compilation for Enabling Tools

TECHNICAL REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the Energy Efficient and Affordable Commercial and Residential Buildings Program. This attachment is a compilation of reports from Project 2.7, *Enabling Tools*, providing supplemental information to the final report (Commission publication #P500-03-096). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is one of 17 technical attachments to the final report, consolidating four research reports from Project 2.7:

- *Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development. NISTIR 6818.* (Oct 2001)
- *Use of the BACnet Data Source in the FDD Test Shell for Testing of FDD Tools in Real Buildings.* (Aug 2002)
- *Development of a BACnet Interface for the Whole-Building Diagnostician (WBD).* (Aug 2002)
- *Results of Testing WBD Features under Controlled Conditions.* (Apr 2003)

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-011). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments, as well as the individual research reports, are also available at www.archenergy.com.

Abstract

Project 2.7, *Enabling Tools*.

As more FDD methods and products become available, selecting the most effective ones will be difficult because of the complexity of products and the lack of repeatability in faults. NIST previously addressed this problem by developing a laboratory, called the Virtual Cybernetic Building Testbed (VCBT), in which controllers and faults could be tested using building simulations. The FDD Test Shell was developed in this project to test FDD methods. These tools were then used to test the Whole Building Diagnostician.

- The project proved that VCBT/FDD Test Shell can independently and objectively assess the capability of new FDD tools quickly in a controlled environment. This tool will allow manufacturers and their prospective customers to test variations of FDD tools required for specific installations.
- The tool will accelerate the acceptance of FDD methods in the marketplace by giving building owners confidence that spending limited budgets on FDD features for their building automation systems will be a good investment.
- Testing of the Whole Building Diagnostician showed that it was successful in detecting eleven of fifteen faults without false alarms under normal sensitivity settings. Two of the undetected faults were due to “climate screening” (for example, a drift in the calibration of a return-air temperature sensor when the outdoor-air temperature and return-air temperature are nearly equal).

This document is a compilation of four technical reports from the research.

NISTIR 6818

Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development

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Abstract

Advances in building automation technology have taken place for a variety of building services including heating, ventilating, and air conditioning (HVAC) control systems, lighting control systems, access control systems, and fire detection systems. In spite of these advances in technology, many building control systems do not work as intended. It is evident that the industry needs to learn how to take advantage of the new ability to interconnect traditionally independent systems in a building. Commissioning, automated fault detection and new approaches to applying system integration are all areas of active research. However, it can be difficult to conduct this research in actual buildings because of the need to maintain comfortable and safe conditions for the building occupants.

This report describes two enabling tools that have been developed to advance these research efforts. It focuses on the use of these tools to develop and test automated fault detection and diagnostic (FDD) technology for HVAC systems and their application in the area of Fault Detection and Diagnosis. The two enabling tools are the Virtual Cybernetic Building Testbed (VCBT) and the FDD Test Shell. The VCBT consists of a variety of simulation models that together emulate the characteristics and performance of a cybernetic building system. The simulation models are interfaced to real state-of-the-art BACnet speaking control systems to provide a hybrid software/hardware testbed that can be used to develop and evaluate control strategies and control products that use the BACnet communication protocol. The FDD Test Shell is a data-sharing tool that was developed to enable side-by-side testing and comparison of two or more FDD tools and to support the integration of information from multiple FDD tools.

Preliminary tests of some of the faults modeled in the VCBT are described in this report. The primary goal of the tests was to quantify the impact of valve and damper leakage for typical air-handling unit (AHU) with variable-air-volume (VAV) box configurations. In this study, testing revealed that leakage through the outdoor air damper and a stuck open outdoor air damper fault have almost no measurable impact on the operation of the system.

Key words: BACnet, building automation and control, direct digital control, energy management systems, fault detection and diagnostics, cybernetic building systems

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1 INTRODUCTION

Building automation and control systems are a special niche in the broad spectrum of distributed computing and control technology. The features and capabilities of building control systems change rapidly, driven to a significant extent by new computing technology developed for other applications with larger commercial markets. State-of-the-art building automation and control systems are characterized by powerful personal computer workstations and intelligent distributed controllers that process complex algorithms quickly and efficiently. The advances in building automation technology have taken place for a variety of building services including heating, ventilating, and air conditioning (HVAC) control systems, lighting control systems, access control systems, and fire detection systems. Adoption of the BACnet®[1] standard [1] communication protocol has made it practical to integrate building control products and systems made by different manufacturers. With BACnet technology it is possible for building automation and control products to exchange information and interact in creative ways that were not practical in the past. A building that uses BACnet technology to integrate various control systems and to connect the building systems to outside entities, such as utility providers, is referred to in this report as a "cybernetic building."

In spite of these advances in technology, many building control systems do not work as intended. In some cases they never did because the design, installation, or commissioning were not done well. In other cases, inadequate maintenance has resulted in a deterioration of system performance over time. Computer hardware and software problems sometimes contribute to the difficulties. Because the ability to interconnect traditionally independent systems in a building is a recent development, there is much that the industry needs to learn about how to best take advantage of this kind of integration. Commissioning, automated fault detection and new approaches to applying system integration are all areas of active research. However, it can be difficult to conduct this research in actual buildings because of the need to maintain comfortable and safe conditions for the building occupants.

To overcome the difficulty of conducting this kind of research using real buildings and outdoor weather conditions, NIST has developed tools that emulate an entire building. This enables building systems research to be conducted under controlled, reproducible conditions. This report describes two enabling tools that have been developed to advance these research efforts. It focuses on the use of these tools to develop and test automated fault detection and diagnostic (FDD) technology for HVAC systems.

The two enabling tools are the Virtual Cybernetic Building Testbed (VCBT) and the FDD Test Shell. The VCBT consists of a variety of simulation models that together emulate the characteristics and performance of a cybernetic building system. The simulation models are interfaced to real state-of-the-art BACnet speaking control systems to provide a hybrid software/hardware testbed that can be used to develop and evaluate control strategies and control products that use the BACnet communication protocol. The FDD Test Shell is a data-sharing tool that was developed to enable side-by-side testing and comparison of two or more FDD tools

[1] BACnet is a registered trademark of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Use of trademark names does not imply recommendation of any commercial products by the National Institute of Standards and Technology.

and to support the integration of information from multiple FDD tools. The objective of the work presented here was to evaluate the effectiveness of the FDD tools for a variety of fault conditions and a variety of weather conditions.

FDD is one of the new features that building controls manufacturers and service providers are likely to offer in the near future; however, a considerable amount of development and testing of FDD tools remains to be performed before this happens. The VCBT is an ideal tool for preliminary testing because data representing both faulty and fault-free operation of HVAC equipment and controls can be produced in a well-controlled simulation environment. The FDD Test Shell further enhances this testing environment by enabling online access to the data through a BACnet interface to the VCBT controllers. To gain access to the data, FDD tools need only be capable of interfacing to the FDD Test Shell, which can be accomplished using a small number of dynamic data exchange (DDE) commands. Thus, a single interface between the FDD Test Shell and the BACnet controllers provides access to the data for multiple FDD tools. This is also an attractive means of accessing data at field sites. Establishing the necessary communication links first in a laboratory environment will help expedite the process in the field.

Section 2 of this report describes the architecture and capabilities of the VCBT in more detail. Section 3 describes the FDD Test Shell and how it can be used to make data from the VCBT or real buildings easily available for testing fault detection algorithms. In section 4 the development of simulation models for commonly found faults in HVAC systems and the incorporation of these models into the VCBT is described. Finally, in section 5 the significance of this work is summarized and plans for the future use of the testing tools are described.

2 THE VIRTUAL CYBERNETIC BUILDING TESTBED

2.1 Overview

"Cybernetics" is defined as the science of control and communication of complex systems. In the field of cybernetics, "intelligence" is determined by the observed conversations (i.e., interactions) among various components making up the cybernetic system.

A cybernetic building system involves energy management, fire detection, security, and transport systems. It may also include interactions with outside service providers, utilities, load aggregators, and emergency services. The VCBT is a tool that provides a way to emulate an entire building, including its various automation and control systems, in the laboratory. It provides a way to examine the interactions of the various systems and to see how the building reacts under adverse events, such as equipment failure or a fire. Tests can be conducted under reproducible, carefully controlled conditions, including weather, without endangering the comfort or safety of occupants in a real building. The VCBT can be used to test new concepts for control strategies and prototype products in a way that is economical, efficient, and convenient.

2.2 Architecture

The VCBT is a collection of computer simulations that are distributed over several computers, and coupled to each other and to commercial building controllers. The controllers are linked to the simulations using a commercial data acquisition system that converts simulated values such as temperatures, pressures, and flows into voltage or current signals that are wired to the controller inputs. The control signals are digitized by the data acquisition system and fed back to the simulations. The overall effect is that the controllers see data that looks like sensor information from real building systems and the simulations respond to the control actions taken by the controllers. Just as a flight simulator simulates an airplane in real time, the VCBT simulates a building, the weather, the HVAC system, and the heating/cooling plant in real time. The VCBT design details are based on experience gained from previous building system emulator research [2]. A photograph of the data acquisition system and control hardware is shown in Figure 2.1.

Figure 2.1. VCBT controller hardware and data acquisition system.

Figure 2.2 shows the components of the VCBT distributed simulation environment. The Center is the heart of the distributed system. It serves as a repository for shared information that is used to couple the simulations, exchanges information with the data acquisition unit, and controls timing. Because real building controllers are used, each simulation must run in real time. The HVACSIM^{+} component is used to simulate the building shell and the HVAC systems. CFAST is a fire simulation program that is used to simulate the effects of a fire in the virtual building. The data logger is the communication interface to the data acquisition system and, indirectly, the real building controllers. The Data Link provides access to a database used to configure the virtual building simulations and investigate information-modeling techniques for representing building system information. The database also contains simulation results that drive the user interface. The graphical user interface (GUI) provides a three-dimensional representation of the building and its component systems and is used to visualize the simulated systems and their responses to control actions.

The common object request broker architecture (CORBA) is used to provide communication between the distributed components of the simulation. CORBA is a vendor-independent, object-oriented architecture that provides a way to link computer programs across a network. The HVACSIM$^+$ and CFAST simulation tools are implemented in FORTRAN. C++ wrappers are used to provide an object-based interface to the simulation programs so that CORBA can be used.

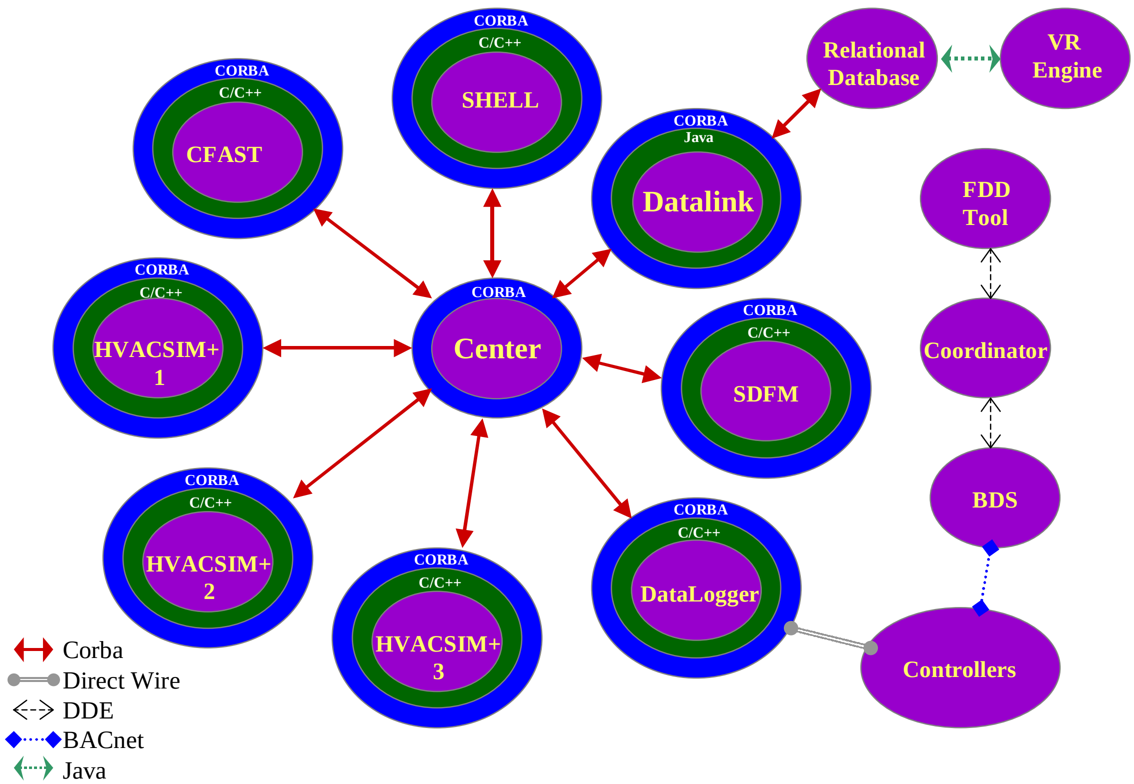

Figure 2.2. Components of the VCBT distributed simulation environment.

The VCBT runs in real-time in a distributed, multi-platform environment. Each component can potentially be run on a variety of machines, except for the data acquisition and control unit which requires special hardware. The platforms used include Windows NT, Windows 95/98, and Sun Solaris. The components use a variety of computer programming languages, including C, Visual C++, FORTRAN, Java, and VRML.

2.2.1 HVACSIM$^+$

2.2.1.1 General description of the HVACSIM$^+$ program

HVACSIM$^+$ stands for HVAC SIMulation PLUS other systems. It is a public domain computer simulation program developed by NIST for studying the dynamic interactions between building system components [3]. This program employs advanced equation solving techniques and a hierarchical, modular approach. The simulation of an entire building/HVAC/control system involves the simultaneous solution of a large number of nonlinear algebraic and differential equations over large time periods using time steps on the order of seconds or smaller. The modular approach is based upon a methodology similar to that used in the TRNSYS program [4]. Variable time step and variable order integration techniques are also used to reduce the amount of computation time required for dynamic simulation. Stiff ordinary differential equations are solved using a solving method based upon the famous Gear algorithm [5].

The HVACSIM$^+$ program consists of a main simulation routine, a library of HVAC system component models, a building shell model, an interactive front end program, and post processing routines. Most of the programs were written in Fortran 77. More recent updates contain specific routines written in Fortran 90. Details of the HVACSIM$^+$ program can be found in its manuals [6-8].

2.2.1.2 Mechanical system component models

The virtual building models a three-story office building and its associated mechanical equipment. Each floor of the building has three zones. The zones on a given floor are served by a dedicated single duct (AHU) with variable-air-volume (VAV) terminal boxes. The AHU dampers, valves, coils, actuators, ducts, and fans, and the VAV box dampers, coils, and valves are represented by HVACSIM$^+$ component models. In addition, all sensors are represented by HVACSIM$^+$ component models. Most of component models (TYPE routines) used in this study were originally developed or revised during the course of ASHRAE 825-RP and described by Haves and Norford [9].

Figure 2.3 is a schematic diagram of a single AHU and the interface of the AHU to the central plant facilities. This figure illustrates the various dampers, valves, actuators, and fans that are controlled. Simulated sensors that serve as inputs to the controllers for AHUs are listed below:

- Mixed air temperature,
- Outdoor air temperature,
- Outdoor air relative humidity,
- Return air temperature,
- Return air relative humidity,
- Return air volumetric flow rate,
- Supply air temperature,
- Supply air static pressure,
- Supply air volumetric flow rate.

The components depicted with dashed lines in Figure 2.3 are not currently modeled in the VCBT.

Figure 2.4 is a schematic diagram of a single duct VAV box and its associated control points. Simulated sensor outputs that are used as inputs to the controller for a VAV box are listed below:

- Zone air temperature,
- Volumetric airflow rate to the zone.

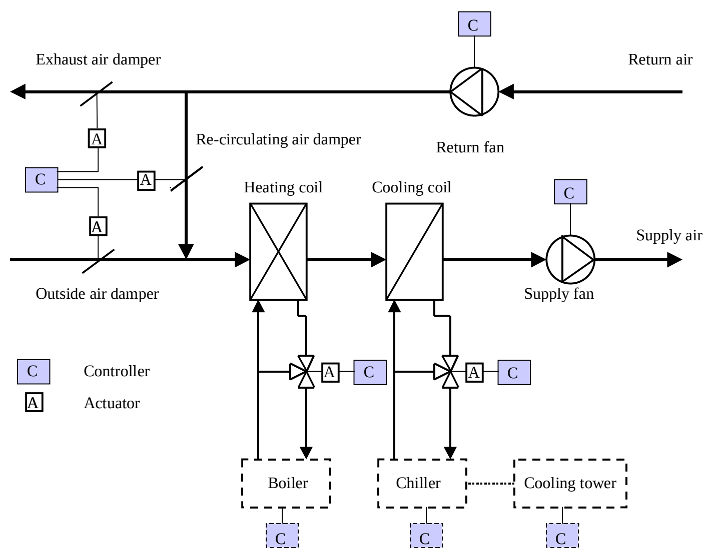

Figure 2.3. A schematic representation of a VCBT air-handling unit.

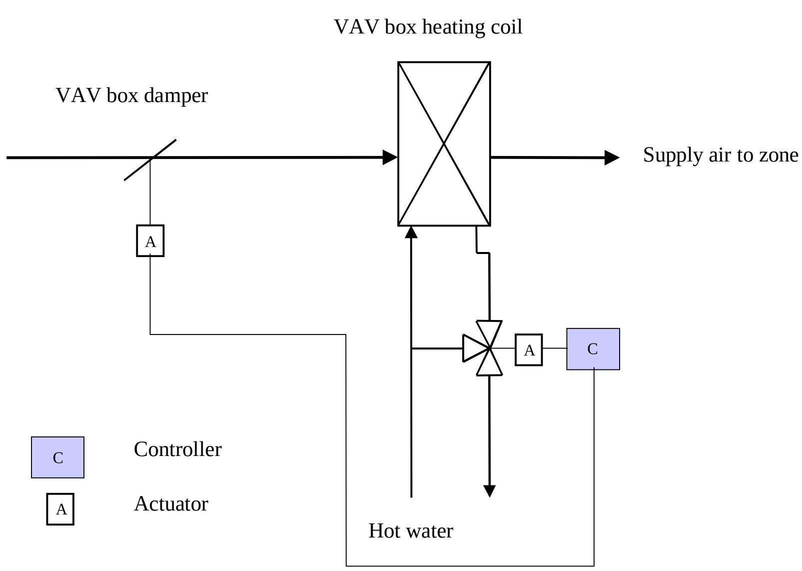

Figure 2.4. A schematic representation of the single duct VAV box.

2.2.1.3 Building Shell Model

A building shell model is included in the VCBT. It can be used to study climatic effects of building location by varying the weather data used for the simulation. In the shell model, heat gains or losses through the building surfaces (walls, ceilings, floors, doors, and windows) due to the outside conditions such as outside air temperatures, solar intensities, and wind speeds are computed. Conduction heat transfer functions are used to calculate conductive heat fluxes of composite multi-layered surfaces [10]. Table 2.1 shows, as an example, the input, output, and user-defined parameter variables associated with building surfaces.

Table 2.1. Building Surface Variables.

Variable	Description
Inputs	
TIA	Indoor air dry-bulb temperature
TMR	Mean radiant temperature
TOSINF	Outer surface temperature of unexposed wall
FAHADW	Shaded fraction of exposed surface
Outputs	
TIS	Inner surface temperature
SOLINT	Integrated solar influx on surface
Parameters	
IZN	Identification number of zone
ID	Identification number of surface
IEXPOS	Internal exposure 0 = within zone, 1= between zones, 2=exposed to sun
ISTR	Identification number of the construct
AS	Surface area
ORIENT	Azimuth angle of normal to surface & south
TILT	Tilt angle: flat roof=0☛, floor=180☛
GRF	Ground reflectivity
IROFS	Outer surface roughness index: 1=stucco, …
ABSOS	Solar absorptance of outer surface
ABSIS	Short wave absorptance of inner surface
EMITIS	Emissivity of the inner surface
TRANSM	Transmittance of the glass window
SC	Shading coefficient of the glass window

2.2.2 BACnet Controllers

Commercially available BACnet controllers make up the building automation and control system of the virtual building. The controllers are wired to patch panels that provide the connections to the emulator. The controllers are connected to each other by various BACnet communication networks. The intention is to eventually have control products from a variety of manufacturers using all varieties of BACnet local area networks (LANs), connected into a single integrated system.

Figure 2.5 shows the network topology of the current BACnet system. For each LAN, the figure shows the type of network technology used and the BACnet network number. An Ethernet LAN serves as the backbone to the system. It connects two operator workstations and the supervisory controllers for the virtual building. These supervisory controllers provide scheduling capability, alarm processing, implement reset schedules and also serve as routers to networks of unitary controllers. The unitary controllers reside on ARCNET or MS/TP LANs. The Device Object Instance_Number of each BACnet device is depicted as ID = XXX, where XXX is the instance number. The medium access control (MAC) address of each controller on the ARCNET and MS/TP LANs is also shown in the figure.

At the present time, the integrated building control system consists of HVAC controls and a fire detection system. Products from three different companies are used. This virtual BACnet building can be made accessible from outside of NIST via a BACnet PTP telephone connection or using BACnet over IP features that allow access from BACnet devices anywhere in the world via the Internet. Future expansion plans include the addition of lighting controls, vertical transport, and access control.

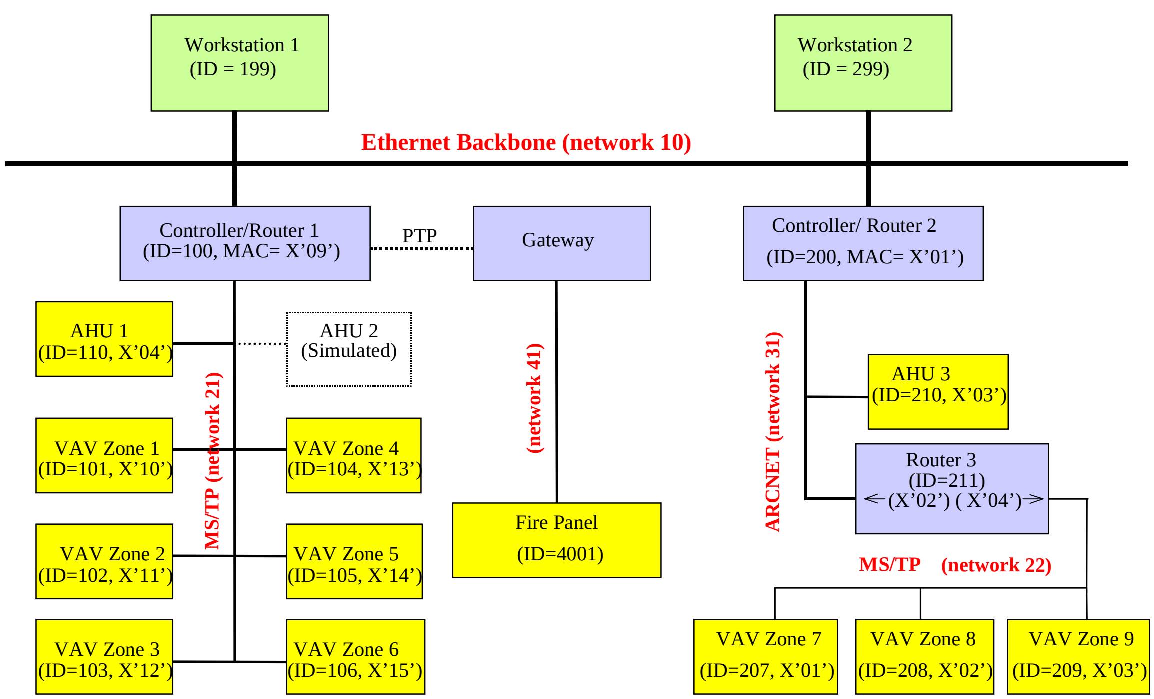

Figure 2.5. Network topology of the BACnet building automation and control system.

Control of air-handling units in the virtual building includes supply fan control, return fan control, supply air temperature control, enthalpy economizer control, and supply air temperature reset. Table 2.2 provides an example BACnet object database for the controller for air-handling unit 1 (AHU 1). AI, AO, AV, BI, BO, and BV denote analog input, analog output, analog value, binary (digital) input, binary output, and binary value objects respectively. There is some variation in the BACnet object databases and control implementation details of the BACnet components. These differences reflect the fact that product features vary from manufacturer to manufacturer. The ranges of sensors and analog values in Table 2.2 correspond to design assumptions about the building equipment operation conditions. These can be varied by AHU or by zone.

Control of VAV boxes in the virtual building consists of damper control and reheat valve control. The damper is controlled to modulate airflow to a zone, while the reheat valve coupled with the reheat coil enables the temperature of air supplied to the zone to be increased. Table 2.3 provides an example BACnet object database for a sample VAV box controller.

Tables 2.2 and 2.3 illustrate the kind of detailed information that is available through a BACnet interface to the VCBT. They also provide the object identifier details needed to access the data using BACnet messages and the scaling details of the connection to the data acquisition system. More complete descriptions of the AHU and VAV box control strategies are provided in section 4.

Table 2.2. Sample BACnet Air-handling Unit Controller Object Database.

Object	Description	Default Value	Remarks
AI-0	Supply Air Temperature	n/a	0 V to 5 V = -17.78 C to 93.33 C (0 F to 200 F)
AI-1	Supply Air Pressure	n/a	0 V to 5 V = 0" to 5"
AI-2	Return Air Temperature	n/a	0 V to 5 V = -17.78 C to 37.78 C (0 F to 100 F)
AI-3	Return Air Humidity	n/a	0 V to 5 V = 0 % to 100 %
AI-4	Outside Air Temperature	n/a	0 V to 5 V = -45.56 C to 65.56 C (-50 F to 150 F)
AI-5	Outside Air Humidity	n/a	0 V to 5 V = 0 % to 100 %
AI-6	Supply Flow Rate	n/a	0 V to 5 V = 0 to 20,000 L/s
AI-7	Return Flow Rate	n/a	0 V to 5 V = 0 to 20,000 L/s
AI-8	Mixed Air Temperature	n/a	0 V to 5 V = -45.56 C to 65.56 C (-50 F to 150 F)
BI-9	Supply Flow Proof	n/a	0 V = Fan ON, 5 V = Fan OFF
BI-10	Return Flow Proof	n/a	0 V = Fan ON, 5 V = Fan OFF
BO-0	Supply Fan	n/a	
BO-1	Return Fan	n/a	
AO-0	Supply Fan Speed	0	0 V to 10 V = 0 % to 100 %
AO-1	Cooling Coil	0	0 V to 10 V = 0 % to 100 %
AO-2	Heating Coil	0	0 V to 10 V = 0 % to 100 %
AO-3	Economizer	0	0 V to 10 V = 0 % to 100 %
AO-4	Return Fan Speed	0	0 V to 10 V = 0 % to 100 %

Table 2.2. Sample BACnet Air-handling Unit Controller Object Database -Continued

Object	Description	Default Value	Remarks
AV-0	Temperature Ctrl Signal	0	
AV-28	OSA Enthalpy	0	
AV-29	Return Enthalpy	0	
AV-40	Min. Return Fan Speed	20	
AV-41	Min. Supply Fan Speed	20	
AV-42	Supply/Return Flowrate Differential	200	
AV-43	Dehumidifying Supply Temp. Setpoint	50	
AV-44	Current Supply Temp. Setpoint	0	
AV-45	Supply Temp. SP Reset Loop	0	
AV-46	Highest Cooling Signal (from VAV's)	0	
AV-47	Supply Pressure SP Reset Loop	0	
AV-48	Current Supply Pressure Setpoint	0	
AV-49	Highest Need More Air Signal (from VAV's)	0	
AV-50	Supply Pressure Setpoint - Warmup	1.4	
AV-51	Supply Pressure Setpoint - Hi Limit	2	
AV-52	Supply Pressure Setpoint - Lo Limit	0.2	
AV-53	Supply Pressure Setpoint - Manual/Startup	1	
AV-55	Supply Temp. Setpoint - Hi Limit	65	
AV-56	Supply Temp. Setpoint - Lo Limit	50	
AV-57	Supply Temp. Setpoint - Manual/Startup	60	
AV-58	Supply Temp. Setpoint - Warmup	160	
AV-60	Supply Temp. Low Limit	50	
AV-66	Econ Min. Position %	15	
AV-80	Humidity Hi Limit	60	
BV-20	Alarm Reset	OFF	
BV-26	Supply Fan Alarm	OFF	
BV-28	Return Fan Alarm	OFF	
BV-32	Economizer Lockout Status	OFF	ON = Econ. locked out
BV-40	Occupied Command	OFF	Starts AHU, Econ. to Min. Position
BV-41	WarmupCommand	OFF	Starts AHU, Econ. stays closed
BV-43	Return Fan Proof	OFF	Transferred from BI-9
BV-46	Supply Fan Proof	OFF	Transferred from BI-10
BV-47	Supply Pressure Setpoint Reset Switch	OFF	ON = Autoreset, OFF = Manual
BV-48	Supply Temp. Setpoint Reset Switch	OFF	ON = Autoreset, OFF = Manual
BV-49	Dehumidifying	OFF	Indicates system is dehumidifying

Table 2.3. Sample BACnet VAV Box Controller Object Database.

Object	Description	Default Value	Remarks
AI-0		n/a	not used
AI-1	Room Temp.	n/a	0 V to 5 V = -1.11 C to 54.44 C (30 F to 130 F)
AI-2	Discharge Air Temp.	n/a	0 V to 5 V =-4.44C to 87.78 C (40 F to 190 F)
AI-3	Airflow Rate	n/a	0 V to 5 V = 0 to 4000 L/s
AO-0	Damper Command	OFF	0 V to 10 V = Full closed to full open
AO-1	Heating Valve Command	OFF	0 V to 10 V = Full closed to full open
AO-2		OFF	not used
AV-0	Heating Signal	0	
AV-1	Cooling Signal	0	
AV-4	Desired Airflow - Cold	0	CFM
AV-6	Occupied Heating Setpoint Offset	0	
AV-7	Occupied Cooling Setpoint Offset	0	
AV-9	Cooling Damper Position %	0	
AV-10	Need More Air - Clg	0	
AV-14	Heating Valve Position %	0	
AV-20	Windsock - Cold (0 to 1)	0	
AV-64	Cooling Damper Time	60	seconds
AV-65	Heating Valve Time	60	seconds
AV-66	Reheat Air - L/s	300	Desired airflow when htg valve full open
AV-67	Max Airflow - L/s	1000	
AV-68	Min. Airflow - L/s	100	Min. air applies only when occupied
AV-90	Occupied Setpoint	72	Limited by AV-91 and AV-92
AV-91	Occupied Setpoint - Hi Limit	80	Limit for AV-90
AV-92	Occupied Setpoint - Lo Limit	65	Limit for AV-90
AV-93	Cooling Offset	1	
AV-94	Heating Offset	1	
AV-95	Unoccupied Cooling Setpoint	85	
AV-96	Unoccupied Heating Setpoint	55	
AV-97	Afterhours Timer Limit	0	Duration for Microtouch
AV-98	Afterhours Timer (hr)	0	Automatically counts down to 0
AV-99	Current Cooling Setpoint	0	Calculated
AV-100	Current Heating Setpoint	0	Calculated
AV-101	Microset Room Temp.	0	Use DDC to transfer AI to this AV
AV-102	Humidity from Microset	0	
AV-103	Outside Air Temp.	0	Transfer from Lsi
AV-104	Mictouch Lever Offset	0	Calculated from current lever position
AV-105	Mictouch Bias Limit	0	Assigned Offset for full stroke
AV-106	Demand Offset	0	Transfer from Lsi

Table 2.3. Sample BACnet VAV Box Controller Object Database -Continued

Object	Description	Default Value	Remarks
BV-0	Bad Sensor Alarm	OFF	
BV-1	Heating/Cooling Mode: On= Heating	OFF	
BV-2	Persistent Communication Fail	OFF	
BV-7	Main Air Status - Cold	OFF	
BV-8	Warm Air in Duct	OFF	
BV-9	Force Min. Air - Cold	OFF	
BV-10	Force Reheat Air	OFF	
BV-11	Force Max. Air - Cold	OFF	
BV-12	Force Open - Cold	OFF	
BV-13	Force Closed - Cold	OFF	
BV-19	Day Mode 2 hour Delay	OFF	
BV-24	Space Too Warm	OFF	
BV-25	Space Too Cold	OFF	
BV-38	Heating Lockout	OFF	Used for demand control
BV-39	Cooling Lockout	OFF	Used for demand control
BV-40	Occupied Command	OFF	Typically sent from Lsi
BV-41	Optimum Start Heating	OFF	
BV-42	Optimum Start Cooling	OFF	
BV-64	Occupied SP's Command	OFF	Turns ON Micset and BV-67
BV-65	OFF Mode Enable	OFF	OFF button ends daymode
BV-66	Afterhour Timer Status	OFF	ON when AV-98 > 0, otherwise OFF
BV-67	Occupied Status	OFF	Determined by BV-64 to BV-66
BV-68	Field Service Lockout	OFF	ON = Field Service Locked out
BV-69	English/Metric display Swap	OFF	OFF = Use VLC Mode, ON = Swap
BV-70	Microset Present Flag	OFF	ON = Microset Present
BV-71	English/Metric VLC Mode	OFF	OFF = English, Read Only

2.2.3 Data Acquisition System

One of the computers used for the distributed simulation contains an interface card that communicates digitally with a commercial data acquisition system. This component is called the "DataLogger" in the system architecture. The simulated values that represent sensor inputs to the controllers are converted by the digital-to-analog converter of the data acquisition system into analog outputs represented by either DC voltages (0 V to 5 V) or DC currents (4 ma-20 ma). There is a capability to scale values to other ranges if needed. The output values of the BACnet controllers that represent inputs to the virtual building system component models are read by the digital voltmeter in conjunction with multiplexing scanners of the data acquisition system. Solid-state relay chips are employed for handling binary (digital) signals between a BACnet controller and the data acquisition system. Figure 2.6 shows the relationship between the data acquisition system with other components of the VCBT. “Hardwire” represents a pair of electrical wires used for analog signals. Other connections are digital communication using CORBA. After receiving data from the computer, converting into the analog values, and sending them to the controllers, the Datalogger waits 1 s, and then begins to read the controller outputs. The total cycle time is 3s to 4 s.

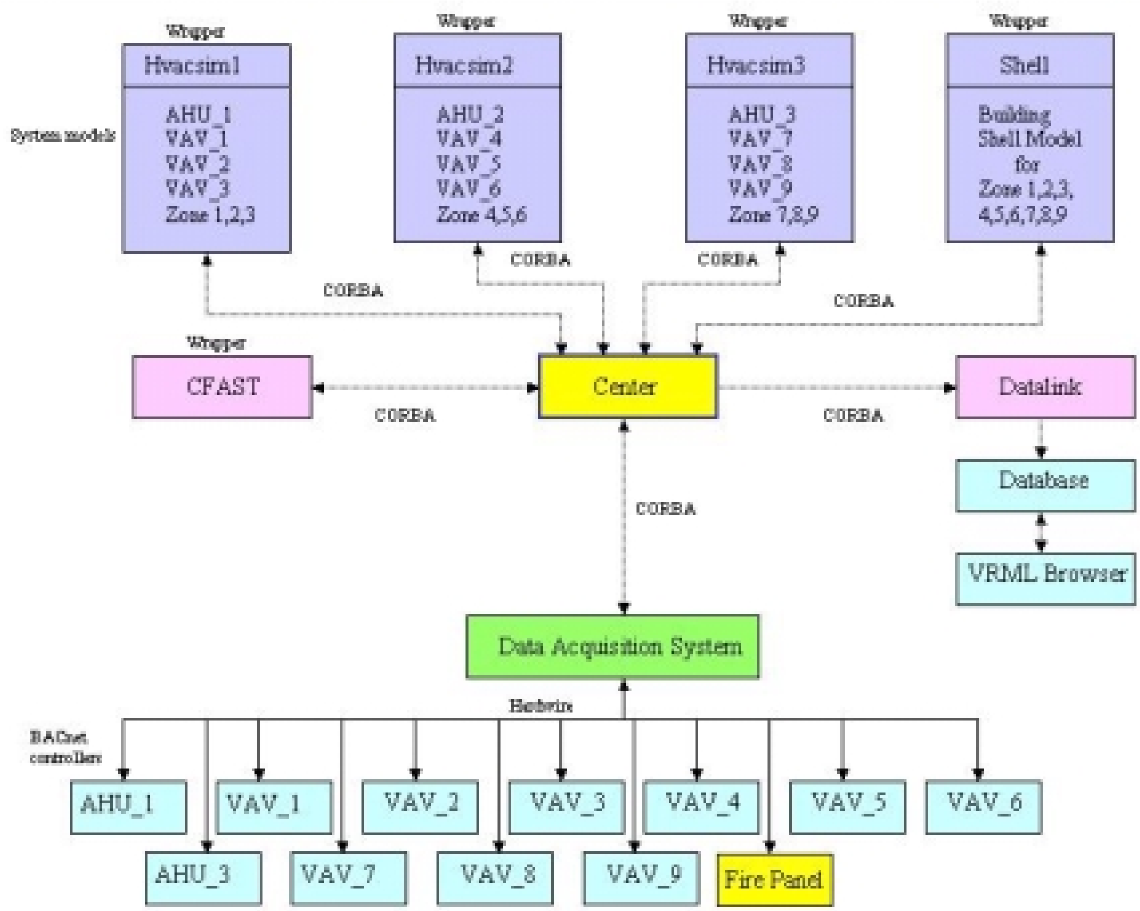

Figure 2.6. Relationship of the data acquisition system with other units.

2.2.4 Center

The Center controls the flow of data between all other elements of the VCBT. It is also responsible for starting, initializing, and closing them. Individual components can be selected for use in a particular run of the VCBT, and the computer that these components will run on can be chosen at runtime.

The user interface to the center is shown in Figure 2.7 for a typical configuration used for FDD testing. In this example only the DataLogger, the HVACSIM$^+$ simulations of the HVAC system components and the SHELL simulation are active. The status of individual components is shown in the section marked "A". A green (light) button indicates that the component is active and a red (dark) button indicates that a component is not being used. The section marked "B" indicates the tasks for each cycle, with the current task highlighted. The most recent data received by the center is shown in section "C". The manual controls for initiating components is shown in the section marked "D."

The Center runs on a 10 s cycle, during which data messages for each active component are created, transmitted, and any return messages evaluated. Time steps in the HVACSIM$^+$ and CFAST simulations are synchronized to correspond to this scan cycle in order to maintain a real-time emulation. The amount of data currently being sent through the Center is only a fraction of its capability.

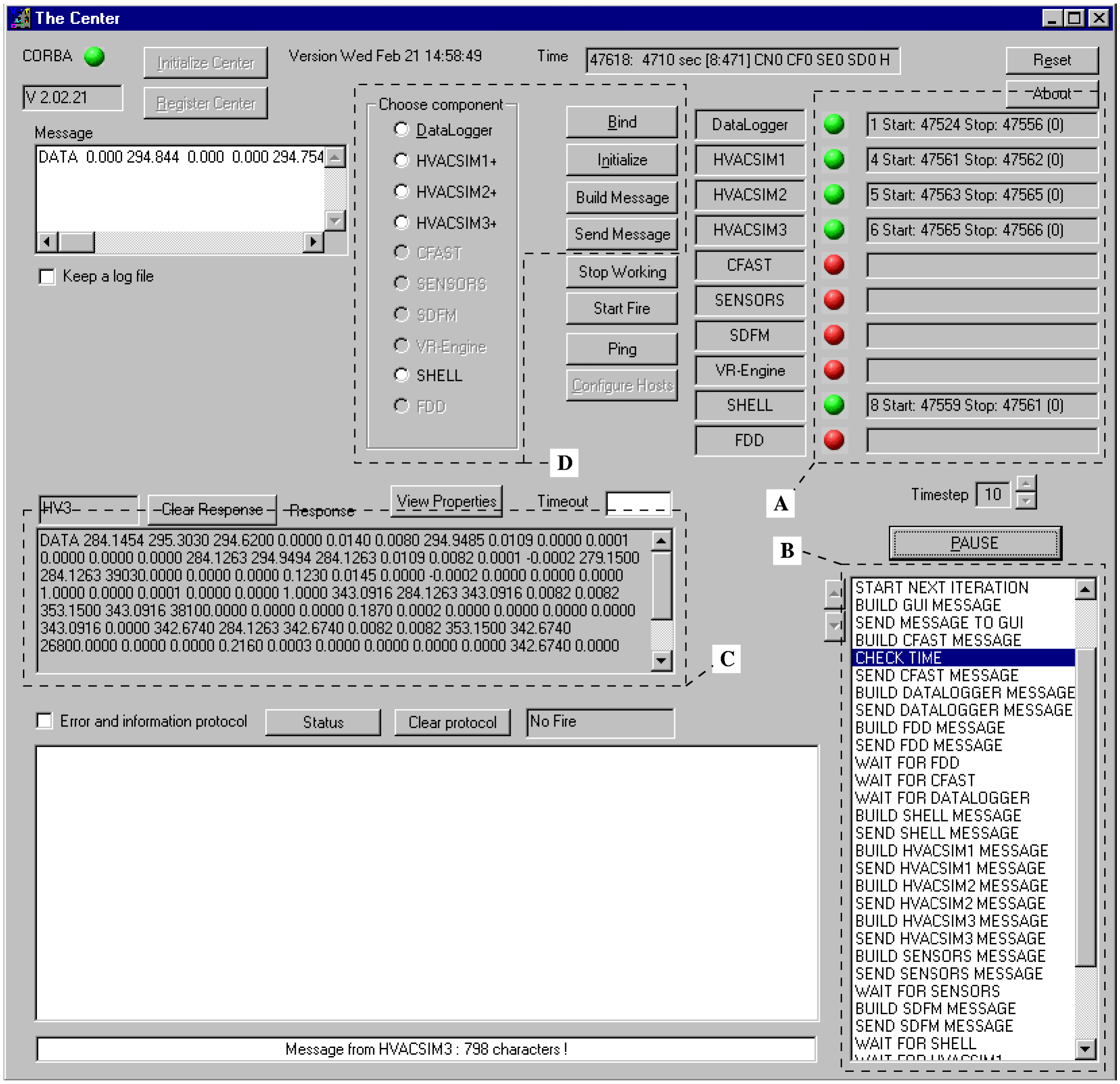

Figure 2.7. The Center Interface. In this example only the DataLogger, the HVACSIM+ simulations of the HVAC system components and the SHELL simulation are used.

The Center is responsible for storing every piece of data that is transferred between the various components of the VCBT. This is done by first creating a list of the objects (i.e. a VAV box or a room) which have properties (i.e. temperature, humidity, set points) associated with them. The properties of each object are then created, and linked to their parent object. For each component of the VCBT, the subset of object and property combinations that the component uses is stored in a list associated with that component. Separate lists are created for each component for data going to the component, and for data coming back from the component. The value of any property used in the VCBT can be viewed at the Center. Figure 2.8 illustrates the tree structure of the Center and the ability to view the value of particular object properties.

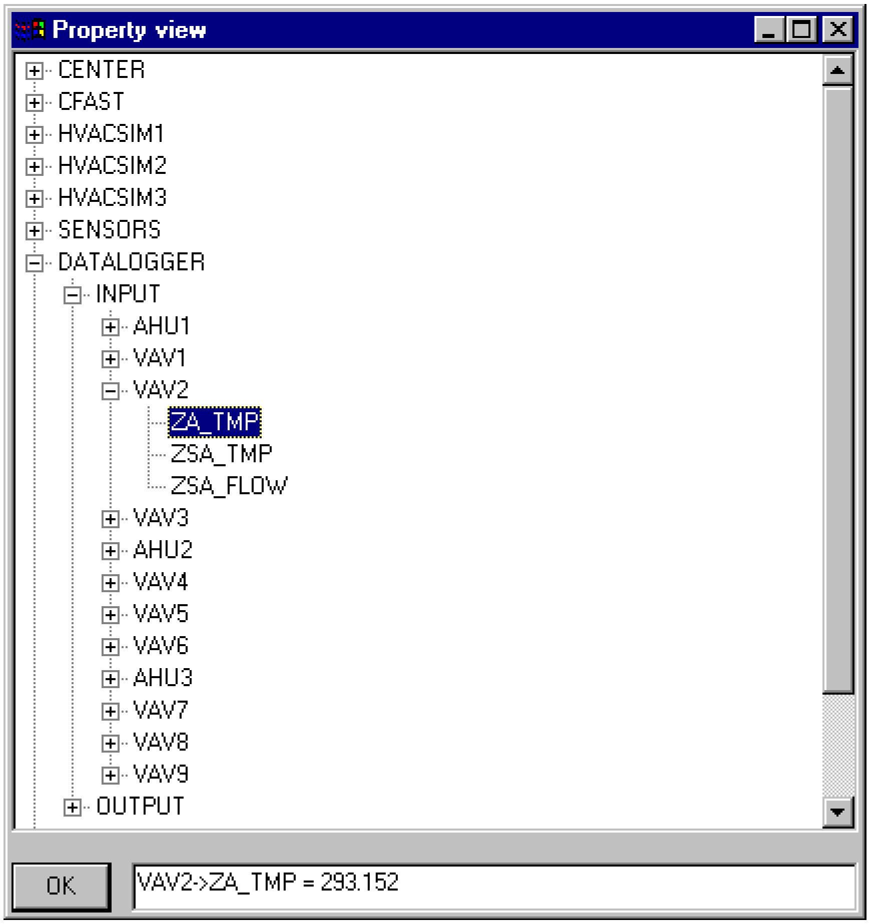

Figure 2.8. Data values can be tracked from the Center.

2.2.5 Graphical User Interface

The graphical user interface (GUI) allows for real-time viewing of the VCBT structure through an interface written in Virtual Reality Modeling Language (VRML). The GUI provides access to data from the rooms, the VAV boxes, and the AHUs available for the most recent cycle and for past cycles. This data is presented in the form of graphs and dials. Also, in the event of a fire in the VCBT, flame size, temperature, smoke density, and the upper smoke layer height are shown through visual cues.

Figure 2.9 is a GUI display showing a perspective view of one floor of the virtual building. The image can be rotated, the walls can be made opaque or transparent, and the user can zoom in on particular rooms or equipment to see more details. Figure 2.10 shows a close-up view of the AHU serving this floor. This display includes live data from the simulations and animation of the mechanical equipment. Figure 2.11 is a similar close-up view of one of the VAV boxes.

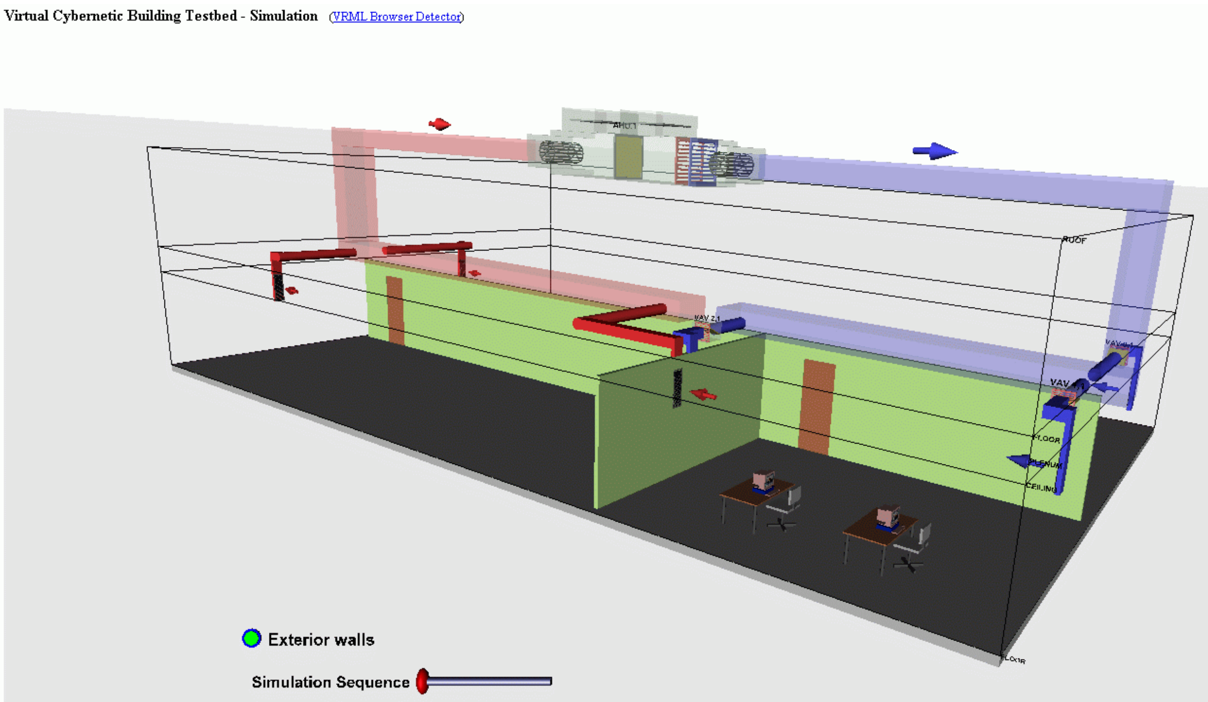

Figure 2.9. Perspective view of one floor of the virtual building.

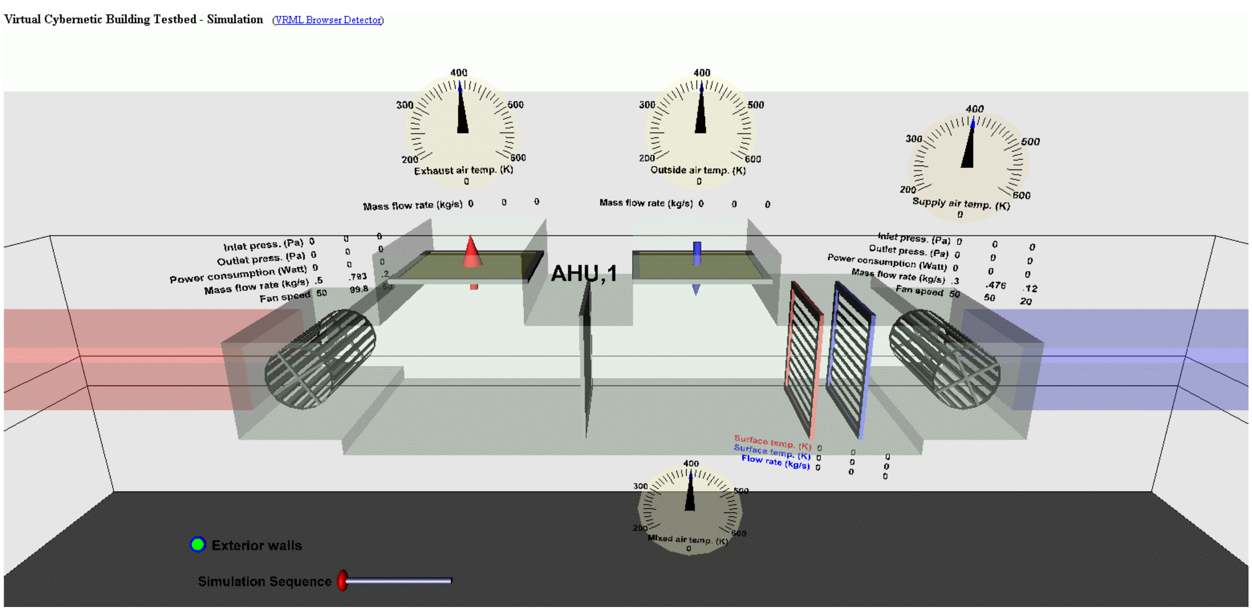

Figure 2.10. Example AHU in the virtual building showing the visualization of live data.

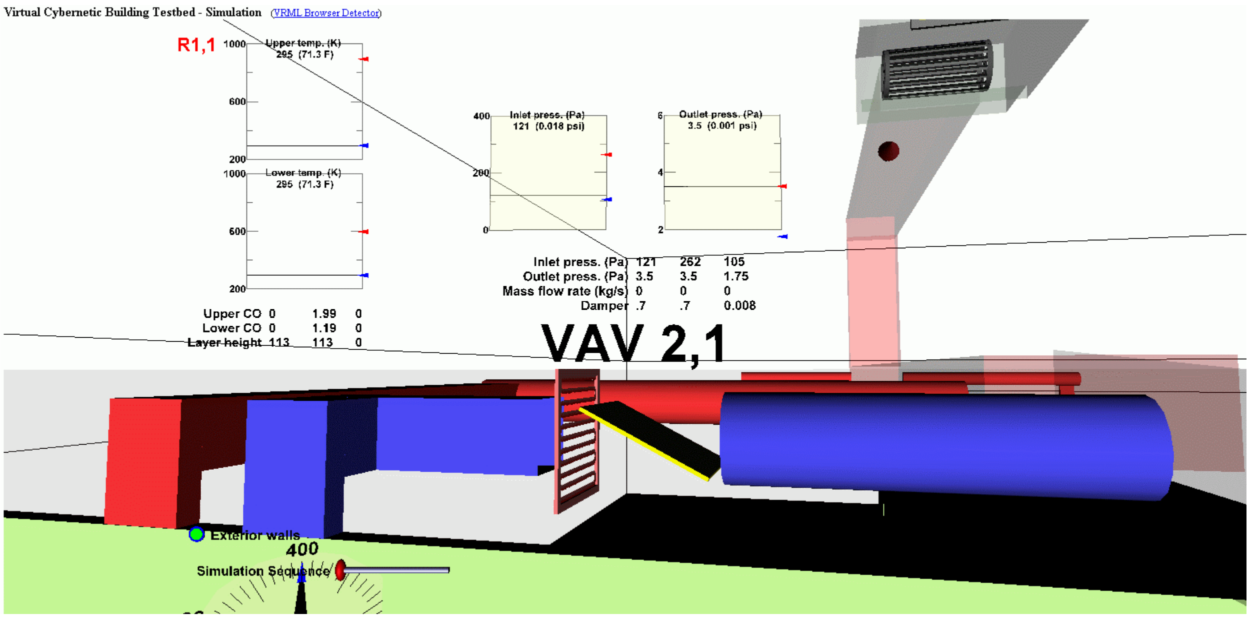

Figure 2.11. Example VAV box in the virtual building showing the visualization of live data.

The GUI consists of three sub-components. The first sub-component of the GUI is called the Datalink. This sub-component is written in Java. The Datalink receives data from the Center, reformats the data, and sends the data to the second sub-component, a relational database. The data is retrieved from the database by the third sub-component, the VRML interface. This relationship is shown in Figure 2.2. The GUI can be viewed and controlled using any VRML-capable browser, typically achieved with a VRML plug-in in a conventional WEB browser.

2.2.6 CFAST

One use for the VCBT is to study the impact of unusual events like a fire. The Consolidated Model of Fire Growth and Smoke Transport (CFAST) model is used to model the behavior of a virtual fire within the VCBT model building. CFAST uses finite element analysis and a set of ordinary differential equations that predict the change in enthalpy and mass over time to predict temperature changes and smoke and gas concentrations. It is a two-zone model, dividing each room into an upper hot layer and a lower cool layer. Each layer is treated as if it were internally uniform, but there can be differences in temperature and smoke and gas concentration between layers. In addition to investigating the impact on building control systems, the ability to create virtual fires is being used to develop new sensor driven fire models (SDFM) that may eventually be incorporated into smart fire panels and used to provide predictive information to assist emergency personnel responding to a fire.

3 THE FDD TEST SHELL

3.1 Overview

The FDD Test Shell is a research tool developed to facilitate testing FDD tools (algorithms). It achieves this goal by separating the task of collecting or generating the process data from the FDD analysis. By standardizing the method used to access data from specific measurements and control signals in the server application, FDD client applications can be configured once to interface to the server application and thereby use the data, regardless of its origin. The Test Shell can obtain the data from many different sources and present it in real time to one or more FDD algorithms through a Microsoft Windows dynamic data exchange (DDE) interface. This allows the researcher to focus on the performance of the FDD algorithm, rather than on the collection or generation of process data, and would enable side-by-side comparisons of different algorithms. Any application development environment that supports DDE can create an interface to the Test Shell.

The FDD Test Shell will be used to interface FDD algorithms to the BACnet controllers in the VCBT. This laboratory experiment will be used to verify the operation of the Test Shell and the ability to interface with real BACnet control systems. The FDD Test Shell interface will then be used for field testing in buildings with BACnet control systems. The field-testing can be done locally (within the building being monitored), or remotely using BACnet's wide area networking capabilities using the Internet Protocols (IP). The BACnet capabilities also provide a method for simultaneously monitoring multiple buildings.

3.2 Architecture

Figure 3.1 illustrates the architecture of the FDD Test Shell. Sections 3.2.1-3.2.3 will discuss the role of each component along with the implementation. In this approach, the modular architecture provides a structured way to share data, models and methods. The Windows DDE platform was chosen because it is commonly available and it allows shared FDD resources to be developed in a variety of application development environments. This includes C++, MATLAB[2], Basic, and spreadsheet programs.

[2] Use of product names does not imply recommendation of any commercial products by the National Institute of Standards and Technology.

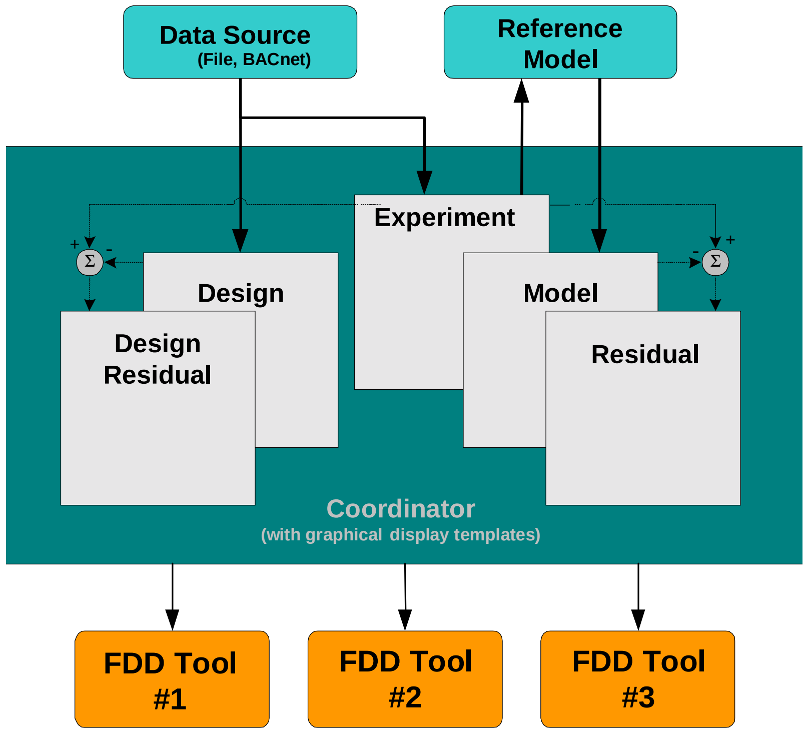

Figure 3.1. FDD Test Shell Architecture.

3.2.1 The Coordinator Program

At the heart of the Test Shell is a DDE server program called the Coordinator. The Coordinator consists of data tables and graphical templates used for displaying data of specific types of equipment. The Coordinator tables, made up of the Design, Design Residual, Experiment, Model, and Residual tables, and the information they contain, are described below.

The Coordinator responds to DDE Advise loops. When an advise loop is requested for a particular Topic/Item, the Coordinator will advise the client program when the cell's time value changes. In the case of both the Design table and the Experiment table, updates come directly from the Data Source program (discussed in section 3.2.2). In the Design table, the coordinator pokes all the available design data values for the building (e.g., system parameters) and provides this data to the FDD tools as requested. In the experiment table, the coordinator pokes contains the complete time series operational data.

The Model table holds predicted values (usually representing normal performance). As the Experiment table is modified, the Coordinator advises the Reference Model program which in turn updates its calculations. When new output reference data is available, the coordinator pokes it into the Model table. However, it is important to note that the Coordinator's Experiment table may be used independently of the Reference Model. For instance, if the implementation of an FDD method has embedded models or does not utilize models of reference operation, raw data can be requested directly from the Experiment table.

As new data streams into the Experiment table and Design table, a series of calculations are automatically made to obtain desired residual values. Specifically, the Residual table reflects the difference between values in the Experiment and Model tables, and the Design Residual table reflects the difference between values in the Experiment and Design tables.

The Coordinator currently includes graphical templates for air-handling units (AHUs) and vapor compression cycles. As time series data streams through the Coordinator, the appropriate graphic is updated to reflect the current values of the available data. The FDD programs can request data from any of the Coordinator's tables or be advised when new data are available. They operate on the data and present results on independent user interfaces. The standard data contained in the templates are described in Section 3.4.

3.2.2 Data Source Program

The Data Source program pokes time series data into the Coordinator. Several different sources can be used as Data Source, including:

- stored trend data files from a building automation system or other source (simulation, laboratory, etc.) (File Data Source),
- stored data from a computer simulation (which may be poked to the Coordinator faster than real-time) (File Data Source),
- real-time data made available by software controlling a laboratory test rig or a building control system (File Data Source), or
- real-time data from BACnet controllers (BACnet Data Source)

The data poked to the Coordinator are time stamped which allows the programs to identify when new data are available. Additionally, the File Data Source program has a utility that allows it to present data from trend files to the Coordinator in faster than real time. To simplify the process of sharing and using data files produced by different individual programs, a data set standard was developed that specifies formatting requirements for the File Data Source program or BACnet Data Source program. The data set standard is provided in section 3.3.

Using the BACnet Data Source program, the FDD Test Shell is used to interface FDD algorithms to the BACnet controllers in the VCBT. BACnet ReadProperty service requests are generated at timed intervals (the default being 10 s) to collect the necessary data from the controllers. The data are poked into the Coordinator's Experiment table for a complete scan cycle that ends with a change to the time stamp cell. The time stamp can be represented in a variety of formats. A mapping feature defines which BACnet property values are inserted into specified Coordinator cells. The program allows for a variety of transformations of data from the input source to the representation needed by the FDD method. The BACnet Data Source program also pokes the design data into the Design table which is in turn accessed by the FDD methods. Most of the operational data is read directly from the controllers, but in the case of design data, a configuration file is used.

3.2.3 Using Reference Models with the Coordinator

The FDD Test Shell allows testing both self-contained FDD methods and FDD methods that require or can use a supporting reference model. Reference models, if used, react to advisories from the Coordinator that new data are available in the Experiment Table. They request input values from the Experiment table, calculate reference or baseline output values, and poke them both into the Model table. The Coordinator calculates the difference between the Experiment and Model tables and inserts the results in the Model Residual table.

This feature facilitates the comparison of different FDD methods using the same reference model. This provides a means of separating the effect of reference models and FDD methods when assessing overall performance.

3.3 Data Standard

To simplify the effort necessary to share data files among Test Shell users, a data set standard was established. The File Data Source program was designed to read data from files that conform to the standard. The following rules define the standard:

1. All the measurements are included in ASCII data files. Each line in the file contains data sampled at different times.
2. The first entry in each line is the time stamp. Several standards are accepted:
   - MM/DD/YY HH:MM:SS.SSSSSS
   - DD.MM.YY HH:MM:SS
   - YYMMDD HHMM
   - Seconds
3. The measurements follow the time stamp on each line and are delimited by any valid ASCII character not found in the ASCII representation of floating point numbers (e.g. "," delimiter makes a comma separated value (.csv) file easily interpreted by Microsoft Excel).
4. The design value for each measurement is included in the first row of the file.
5. Lines starting with the ASCII character "*" designate comment lines.
6. The ASCII string "NaN" is used in place of measurements when no valid numbers are available (e.g. measured value outside of sensor range).

3.4 AHU Template

The Coordinator program is comprised of data cells containing measurements, control signals, set points, etc. at a specified time. To standardise data transfer, an AHU template was established to specify the measurements and units associated with each cell (see Table 3.1). The software implementations of the template include a graphic that displays the time series data in the appropriate physical location. For trend files, the File Data Source program provides a utility for mapping file columns to cells, converting units, and setting default cell values for data not included in the file. A File Data Source configuration file that maps file contents to the appropriate standard template accompanies all standard data files associated with the FDD Test Shell software.

Table 3.1. Air Handling Unit DDE Template.

Cell	Measurement	Units
1	Time	HH :MM :SS
2	Occupancy	0/1 for unoccupied/occupied
3	Supply Air Setpoint Temperature	C
4	Supply Air Temperature	C
5	Return Air Temperature	C
6	Mixed Air Temperature	C
7	Outdoor Air Temperature	C
8	Cooling Coil Inlet Temperature	C
9	Heating Coil Inlet Temperature	C
10	Cooling Coil Discharge Temperature	C
11	Heating Coil Discharge Temperature	C
12	Chilled Water Supply Temperature	C
13	Hot Water Supply Temperature	C
14	Supply Air Relative Humidity	0 % to 100 %
15	Return Air Relative Humidity	0 % to 100 %
16	Outdoor Air Relative Humidity	0 % to 100 %
17	Cooling Coil Inlet Relative Humidity	0 % to 100 %
18	Cooling Coil Discharge Relative Humidity	0 % to 100 %
19	Supply Air Flow Rate	m^3/s
20	Return Air Flow Rate	m^3/s
21	Exhaust Air Flow Rate	m^3/s
22	Outdoor Air Flow Rate	m^3/s
23	Chilled Water Flow Rate (through coil)	m^3/s
24	Hot Water Flow Rate (through coil)	m^3/s
25	Return Fan Power	kW
26	Supply Air Pressure Setpoint	Pa
27	Supply Air Pressure	Pa
28	Cooling Coil Valve Control Signal	0 % to 100 %
29	Heating Coil Valve Control Signal	0 % to 100 %
30	Mixing Box Damper Control Signal	0 % to 100 %
31	Supply Fan Control Signal	0 % to 100 %
32	Return Fan Control Signal	0 % to 100 %
33	Supply Fan Power	kW
34-43	Room Air Relative Humidity	0 % to 100 %
44-60	Room Air Temperature	C

3.5 Interfacing to the Coordinator

The only requirement for interfacing to the coordinator is that the application must be compatible with the Dynamic Data Exchange (DDE) communications protocol. Data Source programs control the collection of data and the flow of data to the Coordinator. The Data Source program intially connects to the Design Table and the Experiment Table of the Coordinator. The Design Table is filled with initial values. The Experiment Table is refilled with data at every time step.

The Experiment Table is filled with data in a two step process. In the first step, all of the data for cells 2-53 are collected and sent to the coordinator via a Poke with the handle string set to ‘all’. The data is formatted as a single text string with the values delimited by spaces. In the second step, the time is sent to the coordinator via a Poke with the handle string set to ‘1’. The time data is formatted as a text string containing the number of seconds past midnight for the current timestep. When the date in cell 1 of the Experiment Table is updated, it will trigger an Advise loop which will trigger the FDD methods, telling them that there is new data available. If a Reference Model program is being used, it will also be triggered. The Reference Model program will then update the Model Table and the Residual Tables.

4 FAULT MODELS

This section describes the faults and fault models implemented in the HVACSIM$^+$ simulation model introduced in section 2. The systems considered are a single duct variable-air-volume (VAV) air-handling unit (AHU) and a single duct VAV box with reheat. Typical sequences of operation and normal operating conditions are described for the systems. The faults considered are then described and the expected impacts of the faults are discussed. Open-loop tests designed to quantify the thermal impact of leakage faults for AHU valves and dampers are also discussed.

It is not practical or even possible to address all the AHU and VAV box systems and the associated sequences of operation and faults that might be encountered in real buildings. The systems described in this chapter are representative of real building applications and are an appropriate starting point for testing and demonstrating FDD tools.

4.1 Air Handling Units

4.1.1 Normal Operation

Figure 4.1 is a schematic diagram of a typical single duct VAV AHU. The AHU consists of variable speed supply and return fans, three dampers for controlling airflow to and from the AHU to the outdoor environment, hydronic heating and cooling coils for conditioning the air, various sensors and actuators, and a controller that receives sensor measurements and computes and transmits new control signals. The operation of the AHU is quite straightforward conceptually. Outdoor air enters the AHU and is mixed with air returned from the building. The mixed air passes over the heating and cooling coils, where if necessary, it is conditioned prior to being supplied to the building. While seemingly straightforward, there are a number of interdependent control loops that dictate system operation. These control loops are summarized in the ensuing discussion. The descriptions of the control loops focus on the strategies implemented in the VCBT; however, in certain cases other common control strategies are also described to make the discussion more general.

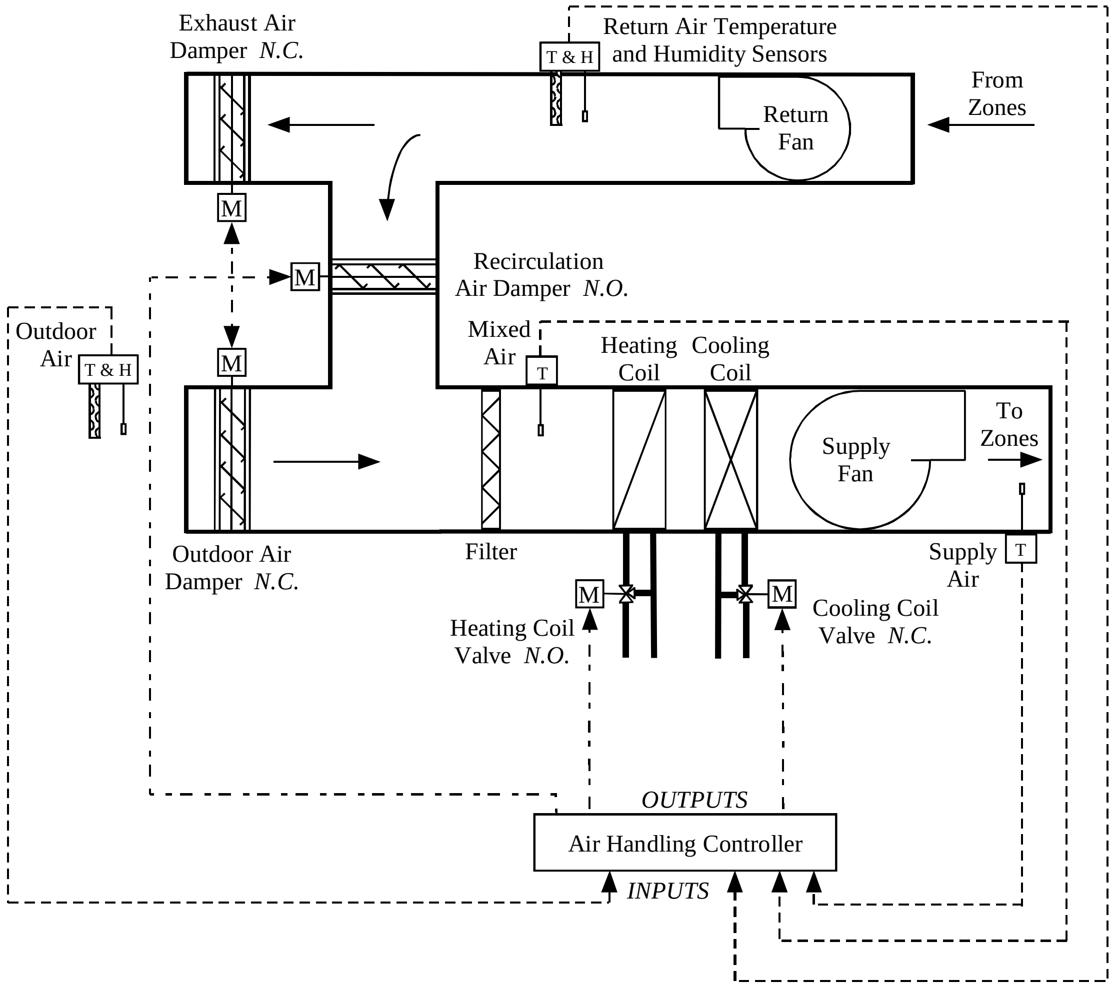

Figure 4.1. Schematic diagram of a single duct air-handling unit.

The supply fan of a VAV AHU is controlled to maintain the static pressure in the supply duct, typically at a constant setpoint value. To accomplish this, the static pressure and its setpoint value are input to a feedback control loop (typically a proportional-integral control algorithm). The output of the control loop is a signal that is used to control a variable speed drive for the fan. Supply air is distributed to various zones (not shown), which may have different loads and setpoint temperatures. To account for the variability of the conditions in the zones, VAV boxes (not shown) that regulate the amount of air that enters a zone are placed at the end of the supply air ductwork leading to each zone. As a zone load decreases, the corresponding VAV box restricts the flow of air to the zone, thereby increasing the static pressure in the supply duct and causing the supply fan speed to decrease in order to maintain the static pressure setpoint condition. If the zone load increases, the VAV box and supply fan respond in the opposite manner.

The return fan is typically controlled to maintain zone pressurization. There are several ways this can be achieved. With the volume matching control strategy employed here, the return fan is controlled to maintain a constant differential between the supply and return airflow rates so that the zones have a small positive pressurization, thus reducing infiltration. Airflow stations (not shown in Figure 4.1) are used to measure the airflow rates in the supply and return air ducts.

AHUs are typically controlled to maintain the supply air temperature at a setpoint value at a location in the supply duct downstream of the supply fan. There are four primary modes of operation used during occupied periods to accomplish this task. Sequencing logic determines the mode of operation of an AHU at any particular time. Figure 4.2 shows a state transition diagram for a finite state machine sequencing control strategy for AHUs (figure taken with author's permission from Seem et al. 1999 [12]). The state transition diagram illustrates the modes of operation and the logic used to transition between modes of operation during occupied times (the terms mode and state are used interchangeably here). Seem et al. (1999) also describe a split-range sequencing control strategy that uses the output of a single control loop to operate the dampers, heating valve and cooling valve in sequence to achieve the desired supply air temperature set point. The purpose and effect of the finite state machine strategy and the split-range strategy are essentially the same, although their implementations differ greatly. The finite state machine logic depicted in Figure 4.2 will be used in this discussion to help illustrate the normal operation of AHUs.

In the heating mode (State 1 in Figure 4.2), the heating coil valve is controlled to maintain the supply air temperature at the set point and the cooling coil valve is closed. The outdoor air dampers are positioned to allow the minimum outdoor air necessary to satisfy ventilation requirements. As cooling loads increase, the AHU transitions from heating to cooling with outdoor air (State 2). In this mode, the heating and cooling coil valves are closed and the mixing box dampers are modulated to maintain the supply air temperature set point. As the loads continue to increase, the mixing dampers eventually saturate with the outdoor air dampers fully open and the AHU changes modes again to mechanical cooling. When the AHU is operating in the mechanical cooling mode, the cooling coil valve modulates to maintain the supply air temperature set point, the heating coil valve is closed, and the outdoor air dampers are either fully open (State 3) or at the minimum ventilation position (State 4) as determined by economizer logic. Economizer control logic often uses a comparison of the outdoor and return air temperatures or enthalpies to determine the proper position of the outdoor air dampers such that mechanical cooling requirements are minimized. For the enthalpy-based economizer used here, the outdoor air dampers are fully open if the return air enthalpy is greater than the outdoor air enthalpy. If the return air enthalpy is less than the outdoor air enthalpy, the outdoor air dampers are positioned for minimum outdoor air.

In many AHU control systems, the supply air setpoint temperature is maintained at a constant value for the sake of simplicity. Reset strategies are also commonly used. The AHU controllers used here have a reset strategy that adjusts the supply air setpoint temperature to satisfy the maximum cooling demand required in any one of the zones during the cooling season. Other reset strategies are based on the return air temperature or outdoor air temperature, with the supply air setpoint temperature being lowered as these temperatures increase.

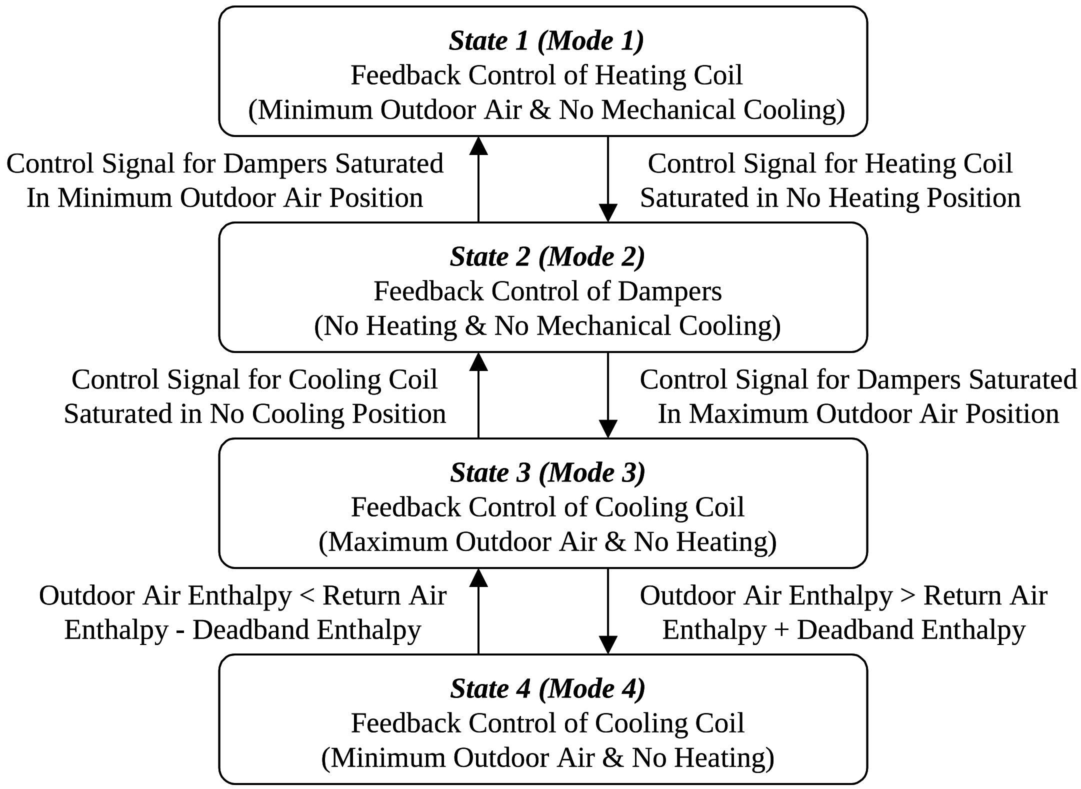

Figure 4.2. Sequencing control strategy for controlling air-handling units (adapted from Seem et al. 1999).

4.1.2 AHU Faults: Implementation and Expected Impact

The faults that have been implemented in the HVACSIM$^+$ code have a thermal impact on the AHU. The faults considered are 1) supply air temperature sensor offset, 2) return air temperature sensor offset, 3) mixed air temperature sensor offset, 4) outdoor air temperature sensor offset, 5) stuck/leaking outdoor air damper (both stuck and leaking faults are simulated, although not simultaneously), 6) stuck/leaking recirculation air damper, 7) stuck/leaking cooling coil valve, and 8) stuck/leaking heating coil valve. These faults are representative of the most commonly occurring faults in AHUs [11

Supply Air Temperature Sensor Offset

- Fault Condition: 0 ºC to –4 ºC
  0 ºC to +4 ºC
- HVACSIM$^+$ TYPE 301: Temperature sensor
- HVACSIM$^+$ Unit: Supply air temperature sensor
- HVACSIM$^+$ Variable: Offset (input for zero output)

The fault (and all temperature sensor faults considered in this chapter) is introduced by linearly increasing or decreasing the temperature sensor model offset parameter (parameter 1) as time increases. The initial offset is 0 ºC, increasing to ±4 ºC over a two week period.

A positive offset will produce an artificially low sensor reading. That is, if the actual supply air temperature is 15 ºC and a +4 ºC offset is imposed via parameter 1 of the model, the sensed temperature will be 11 ºC. The controller wants to maintain the supply air temperature at the set point and will respond accordingly. When cooling is required, this fault will lead to warmer supply air temperatures than anticipated and may also affect the supply air humidity. To compensate for the higher supply temperature, the VAV boxes will open further, leading to increased fan energy use. Conversely, the fault may reduce chiller energy use and may also reduce reheat energy use. Occupant comfort could be sacrificed by higher supply air temperature and humidity levels. In the heating mode it is anticipated that the fault will lead to additional boiler energy use as the heating coil valve must open further to meet the set point.

A negative offset will produce an artificially high sensor reading. This fault will lead to cooler supply air temperatures than anticipated. To compensate for the lower supply temperature, the VAV boxes will close to some degree, leading to reduced fan energy use. The chiller energy use, on the other hand, will increase and in some cases, reheat energy may be needed to offset the lower supply air temperature. In the heating mode it is anticipated that the fault will lead to reduced boiler energy use. However, reheat energy use may increase to compensate for lower supply air temperatures.

Return Air Temperature Sensor Offset

- Fault Condition: 0 ºC to –4 ºC
0 ºC to +4 ºC
- HVACSIM$^+$ TYPE 301: Temperature sensor
- HVACSIM$^+$ Unit: Return air temperature sensor
- HVACSIM$^+$ Variable: Offset (input for zero output)

The fault is introduced as described for the supply air temperature sensor fault. The return air temperature sensor is not universally used for control purposes in AHUs. If it is used, it is used in the economizer logic to determine when to switch from 100 % outdoor air to minimum outdoor air. In the simplest case of a dry-bulb economizer, the return air temperature is compared with the outdoor air temperature. If the return air temperature is the higher of the two readings, the unit will operate with the dampers positioned for 100 % outdoor air. If the return air temperature reading is artificially high, 100 % outdoor air will be used under certain conditions where it would be advantageous from an energy standpoint to use minimum outdoor air. If the return air temperature is artificially low, the opposite effect will occur. Minimum outdoor air will be used under certain circumstances when it would be advantageous to use 100 % outdoor air. In either case there is an energy penalty, with the severity of the penalty depending on the offset.

Mixed Air Temperature Sensor Offset

- Fault Condition: 0 ºC to –4 ºC
0 ºC to +4 ºC
- HVACSIM$^+$ TYPE 301: Temperature sensor
- HVACSIM$^+$ Unit: Mixed air temperature sensor
- HVACSIM$^+$ Variable: Offset (input for zero output)

The fault is introduced as described for the supply air temperature sensor fault. In many systems, the mixed air temperature sensor is not used for control purposes. In these systems, the sensor error will not impact the unit operation. The only impact of the fault would be to reduce its effectiveness as a diagnostic sensor. For instance, if the mixing box damper control signals indicate a call for 100 % outdoor air, the mixed air temperature and outdoor air temperature can be compared to verify proper operation of the dampers. If cooling is achieved using outdoor air (no mechanical cooling), the mixed air temperature and supply air temperature can be compared to verify that the heating and cooling valves are not open or leaking. Of course in the latter case, the temperature rise across the supply fan must be accounted for.

In some systems, a separate control loop may be used to modulate the mixing box dampers to maintain the mixed air temperature at a set point. In such systems, sensor offset may lead to severe energy penalties. For instance, if the mixed air sensor is reading artificially high, the AHU may have to compensate by heating the air using the heating coil. A similar effect would be seen if the sensor is reading artificially low. In this case it might be necessary to compensate by cooling the air using the cooling coil. The AHU model considered in this study does not include a separate mixed air temperature controller. Nonetheless, these examples are raised to reinforce the importance of this particular fault.

Outdoor Air Temperature Sensor Offset

- Fault Condition: 0 ºC to –4 ºC
- 0 ºC to +4 ºC
- HVACSIM+ TYPE 301: Temperature sensor
- HVACSIM+ Unit: Outdoor air temperature sensor
- HVACSIM+ Variable: Offset (input for zero output)

The fault is introduced as described for the supply air temperature sensor fault. The impact of this fault is the opposite of the impact described for the return air temperature sensor. If the outdoor air temperature reading is artificially high, economizer logic will cause the AHU to transition to the minimum outdoor air mode for conditions where operation with 100 % outdoor air is appropriate. If the outdoor air temperature reading is artificially low, the AHU will transition to 100 % outdoor air for conditions where operation with minimum outdoor air is appropriate.

Another impact of this fault would be seen in AHUs that use a reset strategy based on outdoor air temperature to adjust the supply air temperature set point. If the outdoor air temperature sensor reading is artificially high, the supply air set point will tend to be set too low, causing an energy penalty due to excessive chiller use and, perhaps, reheat energy use. The simulation model uses a reset schedule; however, it is not based on a direct measurement of the outdoor air temperature.

Stuck Outdoor Air Damper

- Fault Condition: Stuck open, closed, or at its minimum position
- HVACSIM+ TYPE 321: Motor-driven actuator
- HVACSIM+ Unit: Outdoor air damper actuator
- HVACSIM+ Variable: Position of final control element (0 for stuck closed and 1 for stuck open)

During normal operation, the outdoor air damper modulates when the conditions are right for cooling with outdoor air (State 2), is fully open when the AHU calls for 100 % outdoor air (State 3), and is at its minimum position otherwise. The relationships between the positions of the mixing box dampers under normal operating conditions are shown in Figure 4.3 versus the commanded recirculation air damper position. For these tests, the minimum outdoor air position is 40 % open. The commanded damper position corresponds to the output signal to the damper and may be different from the actual position due to the presence of a fault, hysteresis effects, etc.

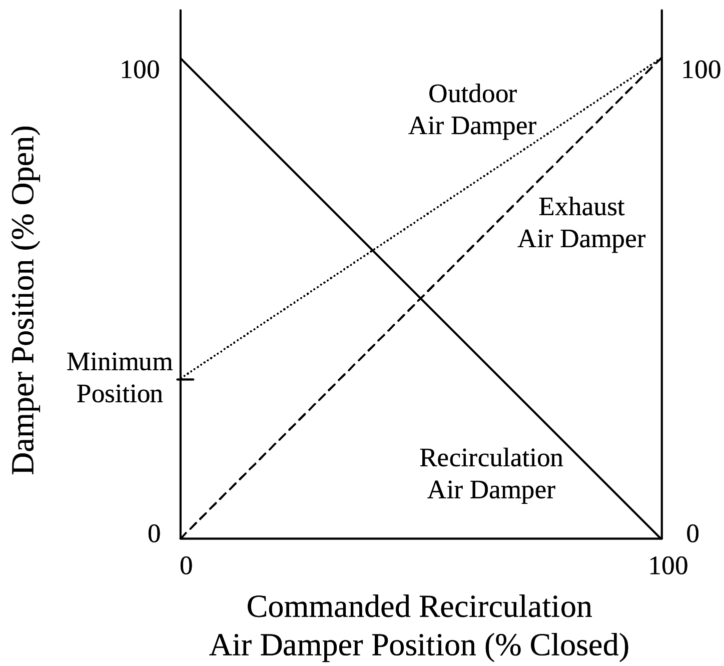

Figure 4.3. AHU mixing box damper position relationships.

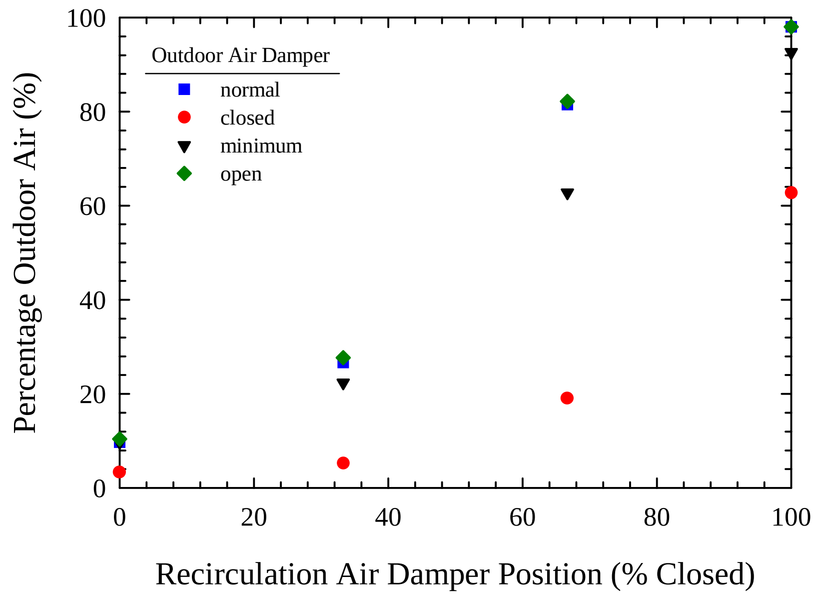

Figure 4.4. Outdoor air percentage versus recirculation air damper position with the outdoor air damper operating normally, stuck closed, stuck at the minimum position, and stuck open.

To consider the impact of a stuck outdoor air damper requires that several cases be examined. Figure 4.4 shows the percentage of outdoor air (mass flow rate of outdoor air divided mass flow rate of supply air multiplied by 100) versus recirculation air damper position for a case where the outdoor air damper operates normally, and for cases where the outdoor air damper is stuck closed, stuck at its minimum position, and stuck 100 % open. For the most part the outdoor air percentage is nearly the same for the fault cases and normal operation. The clear exception is the case where the outdoor air damper is stuck closed. Note the high percentage of outdoor air (approximately 63 %) corresponding to a stuck closed outdoor air damper and a 100 % closed recirculation damper. The large percentage of outdoor air is indicative of a substantial decrease in the supply airflow rate for this case, not of a large increase in the outdoor airflow rate. Because the supply air must be drawn through one of two closed dampers, the supply airflow rate is only 2.2 m^3/s, which is approximately 79 % less airflow than when the recirculation air damper is 0 % to 33 % closed. Hence, when both dampers are closed, the power drawn by the supply fan will decrease considerably due to the decrease in flow delivered by the fan. The supply static pressure will also decrease because there would likely be an extreme negative pressure at the intake to the supply fan.

A less significant fault impact is observed when the outdoor air damper is stuck at its minimum position. The results seem to indicate that furthering testing of the case where the outdoor air damper is stuck open is not warranted because the fault has no observable symptoms. While this conclusion is true for the existing system configuration and control strategy while the AHU is running, stuck open outdoor air damper faults should not be ignored in general. In cold weather, the fault could lead to frozen coils under a number of scenarios. For instance, systems lacking a return fan as well as those designed with a supply and exhaust fan configuration would be susceptible to this fault. The fault could also create the potential for freezing coils when the AHU is not running, regardless of whether the AHU includes a return fan or not.

Leaking Outdoor Air Damper

- Fault Condition: 10 %, 25 %, 40 % of full flow
- HVACSIM+ TYPE 327: AHU mixing box with minimum outdoor damper (minimum damper disabled)
- HVACSIM+ Unit: AHU mixing box
- HVACSIM+ Variable: Leakage for outdoor air damper (0 to 1: fraction of full flow)

This fault was implemented by changing the leakage parameter for the modulating outdoor air damper from its normal value of 0.01 to 0.1, 0.25, and 0.4. The fault is expected to produce increasing values of the fraction of outdoor air when the outdoor air damper is 100 % closed and the recirculation damper is 100 % open. In a normally operating AHU, the outdoor air damper would likely be closed during a morning warm-up cycle, but rarely otherwise. The simulation model used in this study does not include a morning warm-up cycle. Hence, simulations of leaking outdoor air dampers will not reveal symptoms that can be used by a diagnostic tool.

Stuck Recirculation Air Damper

- Fault Condition: Stuck open or closed
- HVACSIM+ TYPE 321: Motor-driven actuator
- HVACSIM+ Unit: Recirculation air damper actuator
- HVACSIM+ Variable: Position of final control element (0 for stuck closed and 1 for stuck open)

This fault is expected to have a significant impact on the outdoor air fraction. If the recirculation damper is stuck open, the fraction of outdoor air will be less than normal when the mixing box dampers are modulating and when the outdoor air damper is 100 % open. This will create an energy penalty, particularly when it is economically advantageous to use 100 % outdoor air. If the recirculation damper is stuck closed, the fraction of outdoor air will be nearly equal to unity at all times because the outdoor air damper will be open to at least its minimum position and the supply fan will draw air through this path. Figure 4.5 shows the percentage of outdoor air versus the commanded recirculation air damper position when the recirculation damper is operating normally, stuck closed, and stuck open. When considering the data in Figure 4.5, it is important to remember the damper position relationships depicted in Figure 4.3. In particular, a commanded recirculation damper position of 0 % closed corresponds to an outdoor air damper position of 40 % open. Hence, the 83 % outdoor air percentage for this situation is not unreasonable.

Leaking Recirculation Air Damper

- Fault Condition: 10 %, 25 %, 40 % of full flow
- HVACSIM+ TYPE 327: AHU mixing box with minimum outdoor damper (minimum damper disabled)
- HVACSIM+ Unit: AHU mixing box
- HVACSIM+ Variable: Leakage for recirculation air damper (0 to 1: fraction of full flow)

This fault was implemented by changing the leakage parameter for the recirculation air damper from its normal value of 0.01 to 0.1, 0.25, and 0.4. The fault is expected to reduce the outdoor air fraction when the modulating outdoor air damper is 100 % open (at this condition, the outdoor air fraction should be nearly equal to unity). This will create an energy penalty during those times when it is advantageous to use 100 % outdoor air. The thermal impact (i.e., how do the changing airflow rates impact the mixed air temperature) of this fault is examined in section 4.1.3.

Stuck Cooling Coil Valve

- Fault Condition: Stuck closed
- HVACSIM+ TYPE 321: Motor-driven actuator
- HVACSIM+ Unit: Cooling coil valve actuator
- HVACSIM+ Variable: Position of final control element (0 for stuck closed)

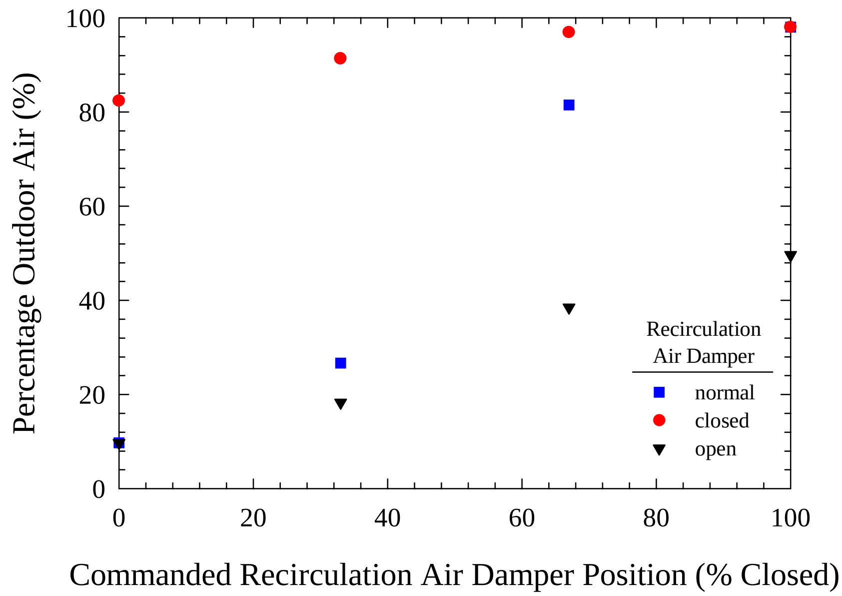

Figure 4.5. Outdoor air percentage versus commanded recirculation air damper position with the recirculation damper operating normally, stuck closed, and stuck open.

A stuck closed cooling coil valve fault is implemented by setting the first output variable for the valve actuator equal to zero. This fault will manifest itself in the inability of the AHU to maintain the supply air temperature at the set point in the mechanical cooling modes. Comfort will be sacrificed due to the fault, but energy use may decrease because the air is not being cooled.

Leaking Cooling Coil Valve

- Fault Condition: 10 %, 25 %, 40 % of full flow
- HVACSIM+ TYPE:524: Coil plus three port valve
- HVACSIM+ Unit: Cooling coil plus three port valve
- HVACSIM+ Variable: Valve leakage (0 to 1: fraction of full flow)

A leaking cooling coil valve fault is implemented by changing the leakage parameter for the valve from its normal value of 0.1e-3 to 0.1, 0.25, and 0.4. The fault is modeled such that its primary impact occurs when the valve is closed. The fault is expected to produce an energy penalty during the heating mode and the cooling with outdoor air mode. In the heating mode the energy penalty takes the form of unnecessary mechanical cooling and extra heating that is required to offset the cooling. In the cooling with outdoor air mode, the energy penalty is due to unnecessary mechanical cooling. It should also be pointed out that the fault forces the AHU to operate in the heating mode under certain conditions that would normally enable the AHU to operate in the cooling with outdoor air mode. The thermal impact (i.e., what is the temperature drop across the cooling coil associated with the leakage) of this fault is examined in section 4.1.3.

Stuck Heating Coil Valve

- Fault Condition: Stuck closed
- HVACSIM+ TYPE 321: Motor-driven actuator
- HVACSIM+ Unit: Heating coil valve actuator
- HVACSIM+ Variable: Position of final control element (0 for stuck closed)

A stuck closed heating coil valve fault is implemented by setting the first output variable for the valve actuator equal to zero. This fault will manifest itself in the inability of the AHU to maintain the supply air temperature at the set point in the heating mode. The absence of heating in the central AHU will be offset by the capability to reheat the air in the VAV boxes. It is unclear what the temperature and comfort implications of this fault will be.

Leaking Heating Coil Valve

- Fault Condition: 10 %, 25 %, 40 % of full flow
- HVACSIM+ TYPE:524: Coil plus three port valve
- HVACSIM+ Unit: Heating coil plus three port valve
- HVACSIM+ Variable: Valve leakage (0 to 1: fraction of full flow)

A leaking heating coil valve fault is implemented by changing the leakage parameter for the valve from its normal value of 0.1e-3 to 0.1, 0.25, and 0.4. The fault is modeled such that the primary impact occurs when the valve is closed. The fault is expected to produce an energy penalty during all modes of operation except the heating mode. In the cooling with outdoor air mode, the energy penalty is due to unnecessary heating. In the mechanical cooling modes, not only does unnecessary heating occur, but additional cooling is also required to offset the load imposed by the heating coil. The thermal impact (i.e., what is the temperature rise across the heating coil associated with the leakage) of this fault is examined in section 4.1.3.

4.1.3 Open-Loop Tests of Select Faults

Evaluating the performance of FDD tools is achieved more readily when the impacts of the considered faults are quantified in a common manner. The temperature sensor faults described in the previous section are all quantified by the temperature offset associated with the fault. In this section, the leakage faults of the recirculation air damper, the cooling valve and the heating valve will be quantified based on the thermal impact of the respective faults. For instance, the impact of a 10% leakage fault for the heating coil valve will be quantified in terms of the temperature rise across the coil. Quantification of the faults will be done by establishing open-loop control modes with fixed inlet conditions.

The previous section described how the primary impact of leakage through the outdoor air dampers is observed during morning warm-up and further pointed out that this mode of operation is not included in the simulation model considered here. Hence, the thermal impact of this fault is not described below.

Leaking Recirculation Air Damper

Leakage through the recirculation air damper is of concern when the AHU operates in the mechanical cooling with 100 % outdoor air mode. In this case, the recirculation damper is closed, while the outdoor and exhaust air dampers are fully open. The fixed open-loop conditions imposed on the AHU are summarized below:

- Recirculation Air Damper: closed
- Outdoor Air Damper: fully open
- Exhaust Air Damper: fully open
- Supply Fan Speed: 100 %
- VAV Boxes: 100 % open
- Return Air Temperature: 21.11 ºC (upstream of the return fan)
- Return Air Humidity Ratio: 0.0078 kg vapor/kg air(upstream of the return fan; at 21.11 ºC, this humidity ratio corresponds to 50 % relative humidity)

Open-loop tests were performed for outdoor air temperatures of 10 ºC, 15 ºC, and 20 ºC. The humidity ratio of the outdoor air was adjusted in each case to achieve 50 % relative humidity. For each outdoor air temperature, tests were performed with return fan speeds of 80 %, 60 %, 40 % and 20 %, which imposed different pressure conditions on the recirculation damper. The results are quantified in terms of the temperature difference between the mixed air and the outdoor air for different leakage values and are shown in Figures 4.6 for a return fan speed of 80%. For no leakage (or more correctly stated, the nominal leakage associated with the fault free model), this temperature difference should be nearly equal to zero. This is borne out by the results. Clearly, the greater the temperature difference between the return air and the outdoor air, the greater the

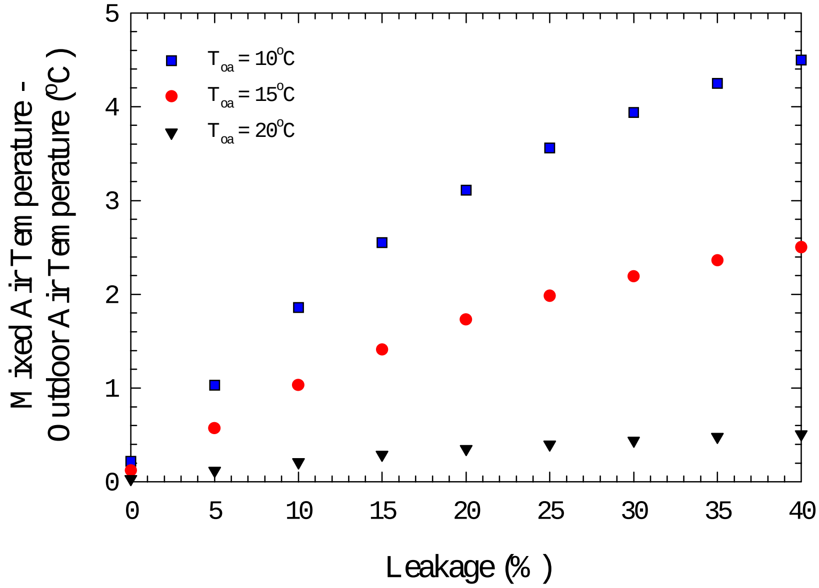

Figure 4.6. Thermal impact of recirculation damper leakage for outdoor air temperatures of 10 ºC, 1 5ºC and 20 ºC.

impact of the leakage fault. It should be noted that the leakage proved to be essentially insensitive to the return fan speed.

Leaking Cooling Coil Valve

Leakage through the cooling coil valve is of concern when the AHU operates in the heating mode and the cooling with outdoor air mode. In these modes, the inlet air temperature to the cooling coil would be expected to be in the range of 15 ºC to 20 ºC. Lower temperatures might be encountered; however, because the chilled water inlet temperature is 6 ºC, the impact of a leakage fault at lower temperatures should be minor. The fixed open-loop conditions imposed on the AHU are summarized below:

- Recirculation Air Damper: closed
- Outdoor Air Damper: fully open
- Exhaust Air Damper: fully open
- Supply Fan Speed: 100 %
- Return Fan Speed: 90 %
- VAV Boxes: 100 % open
- Chilled Water Inlet Temperature: 6ºC

Open-loop tests were performed for inlet air temperatures to the cooling coil of 15 ºC and 20 ºC. The humidity ratio of the inlet air was adjusted for the two cases to achieve 50 % relative humidity. The results are quantified in terms of the temperature drop across the cooling coil at different leakage rates and are shown in Figure 4.7. The impact of the leakage faults will be more significant when the supply fan speed is lower.

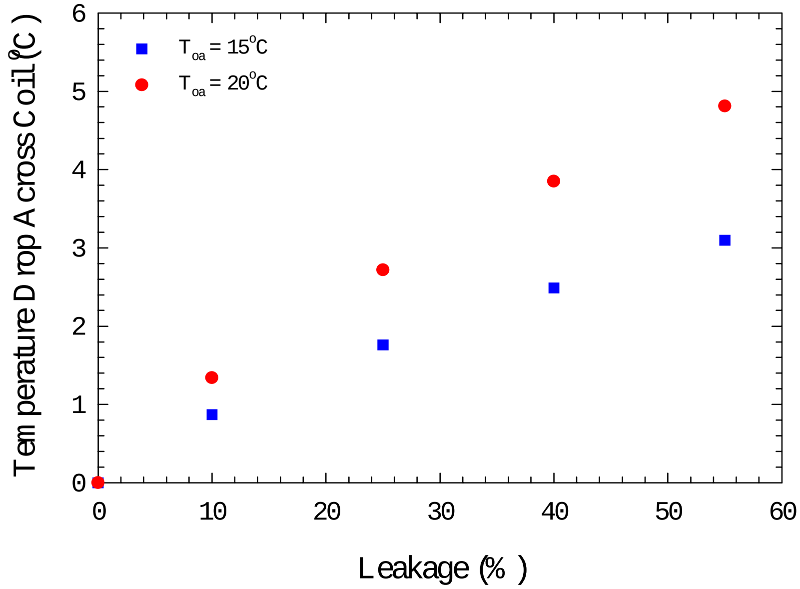

Figure 4.7. Thermal impact of cooling coil valve leakage for inlet air temperatures to the coil of 15 ºC and 20 ºC.

Leaking Heating Coil Valve

Leakage through the heating coil valve is of concern when the AHU operates in the mechanical cooling modes and in the cooling with outdoor air mode. In these modes, the inlet air temperature to the heating coil would be expected to be in the range of 15 ºC to 30 ºC. The higher temperatures would likely be encountered only in applications with high percentages of outdoor air. The fixed open-loop conditions imposed on the AHU are summarized below:

- Recirculation Air Damper: closed
- Outdoor Air Damper: fully open
- Exhaust Air Damper: fully open
- Supply Fan Speed: 100 %
- Return Fan Speed: 90 %
- VAV Boxes: 100 % open
- Hot Water Inlet Temperature: 60 ºC

Open-loop tests were performed for inlet air temperatures to the heating coil of 15 ºC, 20 ºC, 25 ºC, and 30 ºC. The humidity ratio of the inlet air was adjusted for each case to achieve 50 % relative humidity. The results are quantified in terms of the temperature rise across the heating coil at different leakage rates and are shown in Figure 4.8. The impact of the leakage faults will be more significant when the supply fan speed is lower.

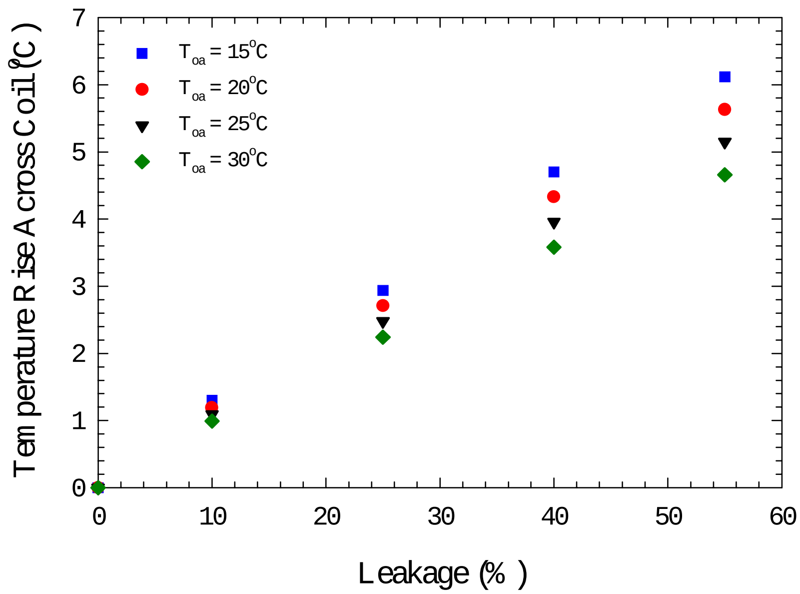

Figure 4.8. Thermal impact of heating coil valve leakage for inlet air temperatures to the coil ranging from 15 ºC to 30 ºC.

4.2 Variable-Air-Volume Boxes

4.2.1 Normal Operation

Figure 4.9 is a schematic diagram of a typical single duct VAV box with hydronic reheat. A typical control sequence is shown in Figure 4.10. The pressure-independent VAV box has a damper for adjusting the flow rate of supply air into the room and a differential pressure transducer (or alternative flow sensor) for measuring the flow rate of air into the room. The air can also be reheated before it is delivered to the room. A hydronic reheat coil is depicted in Figure 4.9, although electric reheat is also common. The thermostat is used to measure the room temperature, and some thermostats allow the building occupant to adjust the set point. Also shown in Figure 4.9 is a temperature sensor that measures the discharge air temperature from the VAV box. This sensor is used to provide diagnostic information rather than for control purposes.

Control systems for pressure-independent VAV boxes commonly use a cascade control strategy to maintain the zone temperature at the setpoint value. A heating set point and a cooling set point are typically specified. As the zone temperature increases above the cooling set point, the airflow rate to the zone increases proportionally. This is accomplished by resetting the setpoint value of the airflow rate and modulating the damper to achieve this flow rate. As the zone temperature decreases below the cooling set point, the damper gradually decreases until it is providing the minimum flow rate necessary for ventilation. If the room temperature continues to decrease and reaches the heating set point, the reheat valve will begin to open. The airflow rate can also be varied in the heating mode, with the airflow increasing as the temperature decreases. Alternatively, a higher fixed airflow rate may be specified for heating operation to improve the distribution of the warm air. In Figure 4.10, it is assumed that a fixed airflow rate associated with the ventilation requirement of the room is provided in the heating mode.

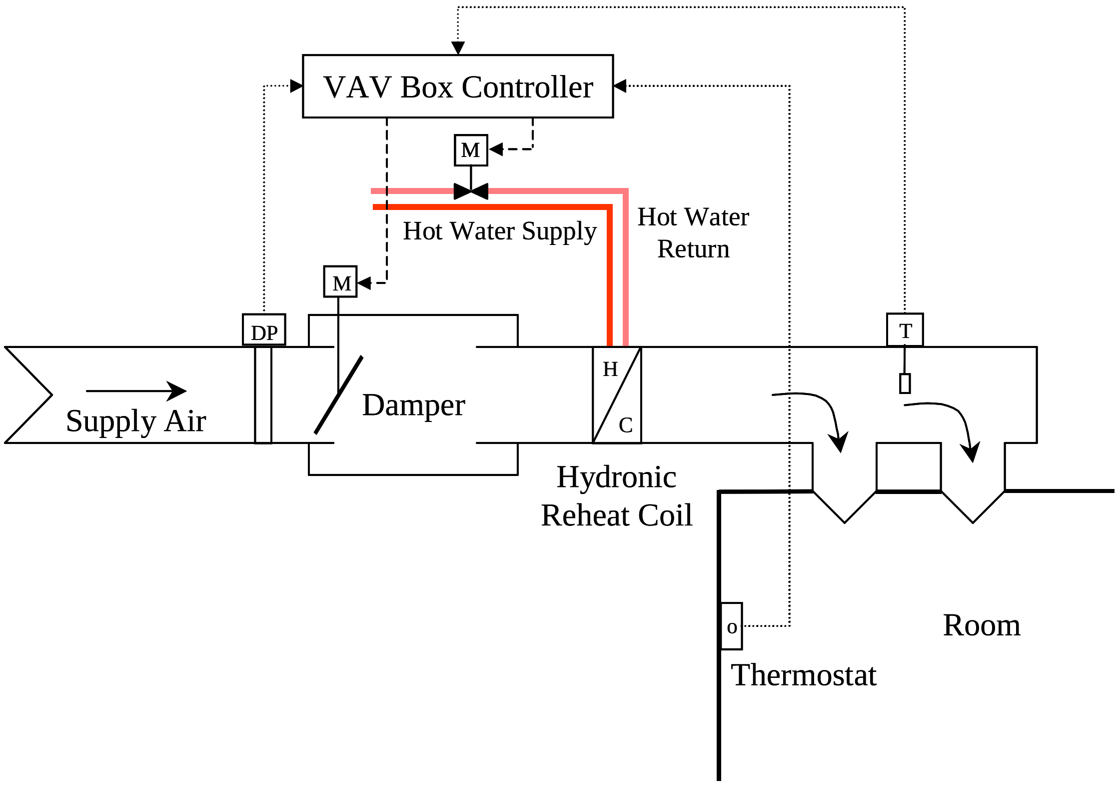

Figure 4.9. Schematic diagram of a single duct pressure-independent VAV box with hydronic reheat.

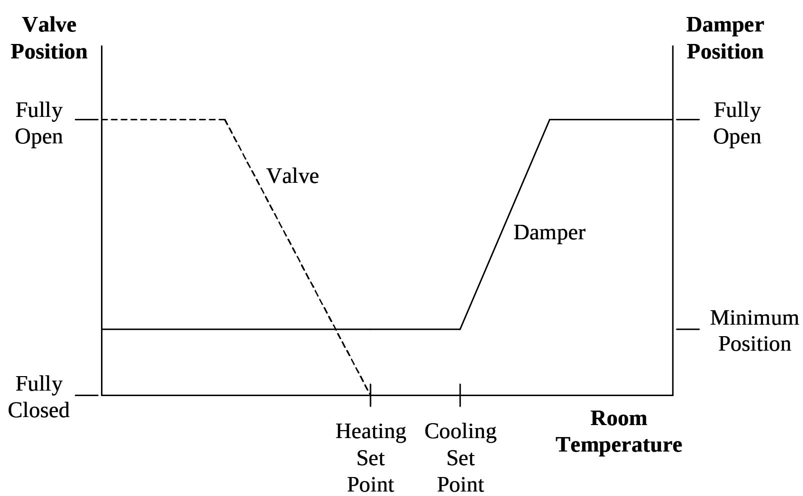

Figure 4.10. Damper and valve control sequence as a function of room temperature for a single duct pressure-independent VAV box with hydronic reheat.

4.2.2 VAV Box Faults: Implementation and Expected Impact

Stuck Damper

- Fault Condition: Stuck open or closed
- HVACSIM$^+$ TYPE 525: Motorized pressure-independent VAV box
- HVACSIM$^+$ Unit: Zone 3 VAV box
- HVACSIM$^+$ Variable: Damper position (0 for stuck closed and 1 for stuck open)

A stuck VAV box damper is implemented by setting the second output variable for the motorized pressure-independent VAV box TYPE to a constant value. When operating normally, the damper modulates to maintain the airflow rate to the zone at the setpoint value. A stuck damper fault will prevent the damper from modulating and will lead to comfort problems as the zone temperature drifts away from the set point. For instance, if the damper is stuck closed on a day that requires significant cooling, the zone temperature will increase because the VAV box is unable to deliver the required amount of cool air. Some AHUs are equipped with a reset schedule that adjusts the supply air temperature downward if a zone is too warm and the damper is wide open. In some cases AHUs are also equipped with a reset schedule that adjusts the supply air static pressure upward if one or more VAV box dampers are wide open. A stuck closed VAV box damper could trigger one or both of these responses because, based on the output signal to the damper, the controller believes that particular damper is wide open. In either case, an energy penalty is incurred.

If the damper is stuck open, occupant comfort could again be compromised. To compensate for the excess air, the VAV box may need to transition to a reheat mode. In addition, the supply fan will have to operate at a higher speed to meet the static pressure set point. Thus, it is clear that both comfort and energy penalties can and do occur when VAV box dampers are stuck open or closed.

Stuck Reheat Coil Valve

- Fault Condition: Stuck open or closed
- HVACSIM$^+$ TYPE 321: Motor-driven actuator
- HVACSIM$^+$ Unit: Zone 3 VAV box
- HVACSIM$^+$ Variable: Position of final control element (0 for stuck closed and 1 for stuck open)

A stuck reheat coil valve fault is implemented by setting the first output variable for the valve actuator equal to a constant value. If the valve is stuck closed and the VAV box is operating in the cooling mode, the fault should have no impact. If, however, the VAV box wants to operate in the heating mode, hot water will be unavailable and comfort may be sacrificed.

If the valve is stuck open and the VAV box is operating in the cooling mode, the damper will be forced to open further in an attempt to compensate for this additional load. This will increase the fan energy use and may jeopardize comfort. In an extreme case, the damper could modulate to the full open position and cause the supply air temperature set point to be reset to a lower value or the supply air pressure set point to be reset to a higher value to compensate for the additional load. In both cases, an energy penalty is incurred. If the valve is stuck open and the VAV box is operating in the heating mode, excessive heating will likely be delivered, forcing the VAV box back into the cooling mode.

5 SUMMARY AND FUTURE WORK

This report provides a description of the VCBT and the FDD Test Shell; two enabling tools developed to advance research efforts related to the integration of building control systems and the development and testing of innovative services such as FDD. The VCBT is a hybrid software/hardware platform that can be used to test new concepts for control strategies and prototype products in a way that is economical, efficient, and convenient. The mechanical equipment and building shell of the virtual building are modeled in HVACSIM+. Control strategies are implemented in real BACnet speaking control products that interface to the HVACSIM$^+$ models through a data acquisition and control unit. Faults associated with sensors and actuators are modeled in HVACSIM$^+$ and their impacts are observed in the responses of the controllers. This provides a convenient and consistent way to generate data that can be used to evaluate the performance of FDD tools embedded in the controllers.

Many of today's emerging FDD tools are stand-alone software products that do not reside in a building control system. Thus, trend data files must be processed off-line, or an interface to the building control system must be developed to enable on-line analysis. The FDD Test Shell provides a platform for standardizing data exchange among various data sources and FDD algorithms that utilize that data. The FDD Test Shell includes a BACnet interface that enables data from BACnet controllers to be accessed and made available to FDD algorithms via a DDE server table. This interface enables FDD tools to be connected to the VCBT's BACnet controllers, thereby providing a testbed for evaluating both performance and communication issues before the more challenging field tests are undertaken.

Preliminary tests of some of the faults modeled in the VCBT are described in this report. The primary goal of the tests was to quantify the impact of valve and damper leakage for typical AHU and VAV box configurations. This was accomplished by performing open-loop tests for faults of varying severity and recording the thermal effect (temperature rise or drop) created by the different faults. The testing revealed that leakage through the outdoor air damper and a stuck open outdoor air damper fault have almost no measurable impact on the operation of the system. The implication of this finding is that further testing of these faults for current system configuration and control strategy is not necessary.

In the next phase of this project, the VCBT and FDD Test Shell will be used for both off-line and on-line testing of AHU and VAV box diagnostic tools for a range of weather conditions. Off-line testing will be accomplished through batch processing of pure simulation data produced by the models embedded in the VCBT and will be pursued because it can be done in faster than real time. On-line testing will demonstrate that the simulated control strategies used to produce data for off-line testing are consistent with the control strategies implemented in the commercial BACnet controllers. It will also demonstrate the robustness of the communication between the FDD tools, the FDD Test Shell, and BACnet products of different manufacturers. This testing will set the stage for interfacing the FDD Test Shell to BACnet controllers in the field and for assessing the performance of the diagnostic tools with field data.

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Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

A Public Interest Energy Research Program
Sponsored by the California Energy Commission

Project 2.7 – Enabling Tools

Task 2.7.2a –Use of the BACnet Data Source in the FDD Test Shell for Testing of FDD Tools in Real Buildings

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National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Introduction

The Fault Detection and Diagnostics (FDD) Test Shell was developed as part of IEA Annex 34. It is a tool that can import building system data in a variety of file formats and make that data available to FDD tools through a Dynamic Data Exchange (DDE) interface. The idea was to make a tool that could speed the development of FDD tools by eliminating the complexity often involved in obtaining and processing trend data from various commercial control systems or output from simulation programs. The BACnet Data Source (BDS) extends the FDD Test Shell capabilities by adding a component that can exchange messages with BACnet controllers as a way to collect the data needed by the FDD tool. The data can be made available in real time or stored in a file for later retrieval and analysis. The interface between the Test Shell and the FDD tool being tested remains the same, thus the details of obtaining data from a BACnet control system are abstracted away in the same way that the details of processing simulation or trend data from other sources was abstracted away in the original FDD Test Shell.

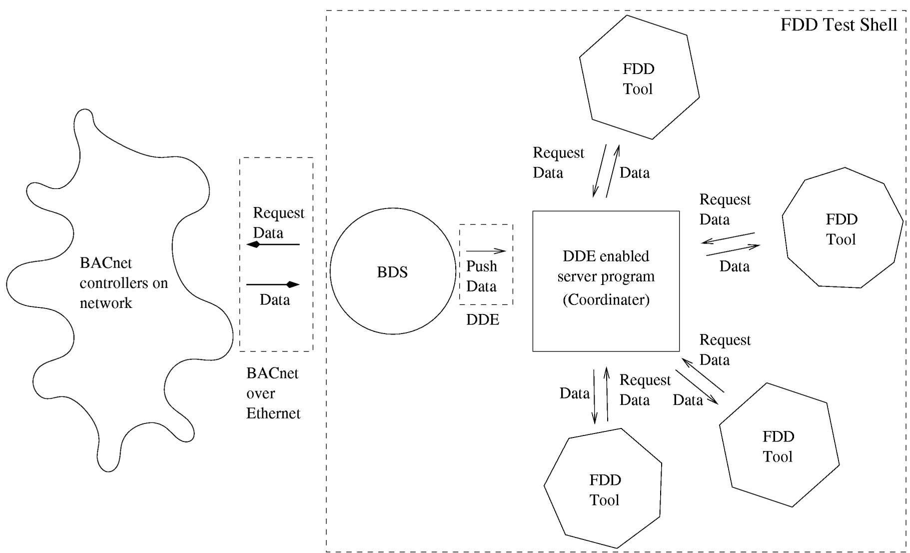

Figure 1- Diagram of BDS functionality

Figure 1 shows how the components of the FDD Test Shell interact. The BDS is designed to run on a personal computer with an Ethernet network interface card. It assumes that at least one part of the BACnet system uses an Ethernet local area network (LAN) that can serve as the connection point to the entire system. Data from BACnet controllers that reside on other BACnet subnetworks are obtained by communicating through the BACnet routers that are part of the control system. In this project the BDS was used with BACnet controllers in the Virtual Cybernetic Building Testbed. In principle, it could also be used in any real building that has a BACnet control system with an Ethernet LAN.

Description

The FDD Test Shell is comprised of three main parts: a data source, a data coordinator, and one or more FDD logic components. The data source can be one of several input file types or the BDS. The data source provides data to the coordinator at configurable time intervals. The coordinator alerts the FDD logic components when new data is available and they access the data through the DDE interface. The FDD logic components are the tools that are being evaluated. If multiple logic components are used they may process the same data with different rules or techniques, or they may process data from different HVAC controllers. For this project there was only one logic component used, called the AHU Performance Assessment Rules (APAR). APAR was implemented as a MATLAB module.

The BDS works by sending BACnet ReadPropertyMultiple requests to the building controllers. The requests currently can be for the Present_Value property of Analog Input, Analog Output, Analog Value, Binary Input, Binary Output, and Binary Value objects, or for the Local_Date or Local_Time properties of a Device object. The data points to be retrieved by the BDS are determined by reading a configuration file at startup. The configuration file is divided into two sections. The first section lists the data points to be retrieved and the second section lists the location and names of files in which the data are to be stored. A useful feature of BDS is that subsets of the data points can be saved in separate output files, and any single data point can be saved in more than one output file. If a data point expected by the FDD Test Shell is unavailable, a placeholder or dummy value may be included in the data file to fill in for the missing value. A value of –999.9 will be stored for the missing value.

Configuration File Format

A sample configuration file is shown in Figure 2. In the first section of the configuration file, each line represents one data point that will be read by the BDS.

```
1       2       3       4             5             6       7
BV,     48,     31,     A0B0C0D0E0F0, 03,           1,      "Cause 18"
BV,     49,     31,     A0B0C0D0E0F0, 03,           2,      Cause 19
LD,     200,    0,      X,            A0B0C0D0E0F0, 0,      "Local Date"
LT,     200,    0,      X,            A0B0C0D0E0F0, 0,      "Local Time"
DU,     0,      0,      X,            0,            1,      "Placeholder"
AO,     141,    31,     A0B0C0D0E0F0, 02,           1,      "Z1 Airf. Cont."
AO,     142,    31,     A0B0C0D0E0F0, 02,           2,      "Z1 Reheat Coil Cntl."
END
DIR c:\data\      8
FILE file1.dat, 10    9    Second Section                    First Section
FILE file2.dat, 60
END
```

Figure 2 – A sample configuration file

The components of a line are:

1. Object-Property Listing: This entry must be selected from Table 1.

Entry	Object Type
AI	Analog Input
AO	Analog Output
AV	Analog Value
BI	Binary Input
BO	Binary Output
BV	Binary Value
LD	Device, Local_ Date
LT	Device, Local_Time
DU	Placeholder Value

Table 1- Object Types for configuration file

   In BACnet, Local_Date and Local_Time are properties of the Device object, but for the purposes of BDS they are designated as separate entries above. For the other BACnet objects listed, the Present_Value property is used.

2. Object Instance: This is the instance number of the object. For example, if you want to read Analog Input number 4, this entry would be a 4.

3. Controller Network: This is the destination network address (DNET) of the controller containing the requested object. If the controller is on the same network as the computer running BDS, set this value to 0.

4. Router MAC Address: Enter the MAC address in hex of the first router to the controller network. If a router MAC address is not needed, enter an X instead.

5. Controller Address: Enter the MAC address of the controller here, in hex.

6. File Control Mask: This field controls where the data values are stored. A data value can be designated to be sent to the coordinator (or another DDE speaking program), or to any of up to eight separate files. The files are designated in the next section of the configuration file. This field operates as a bitmask, with the fields designated in Table 2. The value for the file control mask is the sum of the desired values in Table 2. It is not necessary to use or designate every file listed in Table 2. If the file control mask for a data point is set to save to a file that is not defined in section 2 (or a file which is later removed from the configuration file) the data point will still be saved to other files set by the file control mask. It should be noted that the Local_Date and Local_Time values, if designated, will automatically be saved to every data file, and the file control mask for those data points should be 0 to avoid duplication.

Value	Action
1	Sent through DDE, and saved in file 1
2	Saved in file 2
4	Saved in file 3
8	Saved in file 4
16	Saved in file 5
32	Saved in file 6
64	Saved in file 7
128	Saved in file 8

Table 2- File control mask values

Example: If a data point is to be saved in files 1, 3, and 6 then the file control mask for that data point would be 1 + 4 + 32 = 37.

7 Text Label: A descriptive label may be added to provide information about the data point. This label is used as a column heading for files in which values for this data point are stored. The label may be up to 40 characters long. Quotation marks surrounding the text are not necessary and will be removed from the text.

A line starting with the keyword END denotes the end of the first section. There may be up to 200 data points listed in the first section. For placeholder or dummy data points, only the Object-Property Listing, File Control Mask, and Text Label fields are used. The other fields must be present, but may contain any in-range values.

The second section of the configuration file describes the data files saved by BDS. There can be up to 8 files saved, each containing a subset of the data points. Data points can be saved to multiple files. There are two settings in the second section:

8 The first setting contains the directory in which the data files are to be stored. This setting is optional. If it is not included the default save directory is c:\. This setting is specified by starting the first line in the second section of the configuration file with the keyword DIR, followed by the directory in which the data files are to be saved, e.g., C:\data\. This setting is shown in the sample configuration file in Figure 2. If the directory entered is not usable, the directory will default to c:\.

9 The second setting describes an individual data file. This setting is specified by starting a line with the keyword FILE, followed by white space, then the filename with extension, a comma, and a number representing the interval in seconds to update the file. This number should be in the range from 10 to 3600. The first file will contain all the data from data points with a file control mask containing 1, the second file will contain all the data from data points with a file control mask containing 2, and so on up to 8 files.

A line starting with the keyword END also denotes the end of the second section. Any text placed after the end of section 2 will be ignored by BDS, allowing comments or other information to be placed there.

Details of data files

The data collected by the BDS can be saved into several files. The file name, directory, list of data points, and the interval to save the data points are given in the configuration file. The file directory can be changed at runtime by entering a new directory name in the Log File Location box. The save interval for each file can also be changed at runtime by entering a new interval, in seconds, in the appropriate Data File Timer box. The data values are saved to the data files in the order they are listed in section 1 of the configuration file, and are separated by commas (CSV format). Before any data is written to the data files, the label fields are written to the files to serve as column headings. The data that are saved in the first file (set by file control mask) are also sent to the DDE component at each interval, again in the order that they are listed in section 1 of the configuration file. There may be up to 8 data files specified. The data points that are listed for the first file are also sent to the DDE component. Old data files are not deleted by the BDS, and new data will be added to them until the user moves them.

Using the BDS

The first step is to determine the list of data points that will be recorded. This will usually be dictated by the requirements of the FDD tools being tested, although additional data points that are not available through the DDE interface may be recorded by the BDS. There may be up to 200 data points total, from multiple controllers on different networks. The data points may contain data from Analog Input, Analog Output, Analog Value, Binary Input, Binary Output, or Binary Value object Present_Value properties, or the Local_Time or Local_Date from the Device object. It is suggested that data points from the same controller be grouped together to take advantage of the ReadPropertyMultiple capability of the BDS. If the FDD Test Shell is expecting values that are not available from the controllers, a placeholder or dummy value may be included in the configuration file with the file control mask set to include the first data file. The second step will be to determine the files to be saved by BDS and which data points will be saved to which files. Once that is done, the settings file can be created. The settings file must be in text format. The file name must only contain characters allowed for a file name. There are no other limitations on the name or file extension given to the settings file. The next step is to start the BDS. Figure 3 shows BDS after it is opened. After BDS is opened, the name and location of the settings file must be entered in the box in the 'Select Level to Monitor' area, as shown in Figure 4. The default file name is c:\custom.bif. The path and filename together must less than 80 characters long. When the full path and filename are entered, click on the 'Custom Floor' button to have the BDS read in the settings file. If there are any errors in the settings file, an error message will appear in the status window. After the settings file is read in, the Datapoint Values area will show the data points from the settings file and the Data File Timers area will show a box for each data file containing the update interval for that file. The update interval for a data file may be changed to any number of seconds in the range 10 to 3600 by typing a new number in the box for that data file. Because the first data file listed in the settings file determines how often the data is updated, it is suggested that subsequent data files have an update interval equal to or larger than the update interval for the first data file to avoid over sampling the data.

After the settings file has been read, the next step is to initialize the BACnet interface. This is done by pressing the button labeled “Init BACnet” in the control button area of the BDS

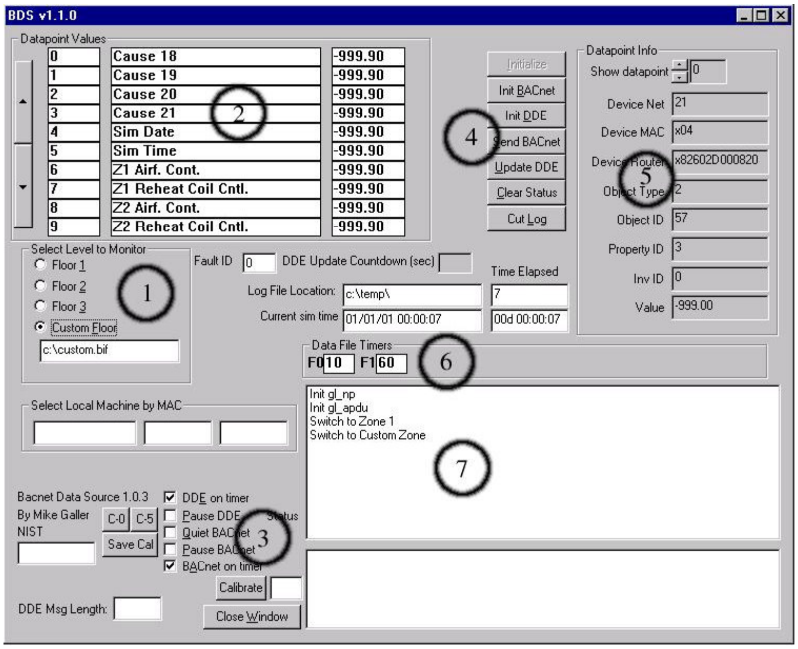

Figure 3: View of the BDS when opened.

1: Click Custom Floor to read in settings file

2: The data points will be displayed here

3: Settings for BDS

4: Controls for BDS

5: Details on data points viewed here

6: Details on data file timers viewed here

7: Status window displays events and error messages

interface. If there are any errors, an error message will appear in the status window. This step will also start the timers used to control the data files. If data is not being sent to the Coordinator (i.e. only saving data to file), then this is the last step until data collection is finished.

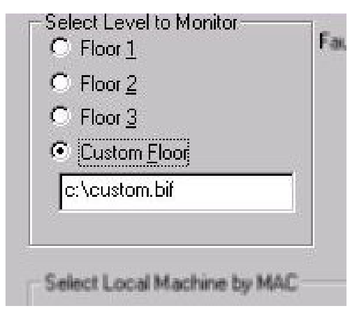

Figure 4- Enter the name and location of the settings file

If data is being sent to the Coordinator, then the DDE interface will also need to be initialized. The Coordinator must be started, then press the button labeled “Init DDE” which is right under the “Init BACnet” button. This will establish a connection to the Coordinator. At this point, data collection and passing will have begun, and no further action is needed until data collection is finished.

Format for output data files

The format for the output data files is consistent across all data files. The variables are saved to the data files in the order they are specified in the configuration file. Each file will start with a row of column headings, consisting of the data label for each data point designated to be saved into that file. The second line will contain the string "data = [" which is intended to assist with importing the data files into Matlab. The data starts on the third line. The format for each line begins with the date as read from a controller in YYMMDD format, then the time as read from a

```
Date, Time, Cycle, Occupancy, Spy. Temp Setpoint, Spy. Air Temp
data = [
010201, 0630, 38.00, 00.00, 15.56, 12.35
010201, 0631, 96.00, 00.00, 15.56, 12.19
010201, 0632, 153.00, 01.00, 16.11, 10.98
]
```

Figure X- A sample data file, starting 6:30 A.M., Feb. 1, 2001

controller in hhmm format, then the cycle counter, which records the number of seconds elapsed since data collection began. These are followed by the data points listed in the configuration file, with every variable separated by a comma. If there is no time and/or date data point listed in the configuration file, then the current time and date on the host computer will be used. The last line of the data file will contain a right bracket, "]", again to assist with Matlab. The data files will be renamed with a time/date stamp when the date being saved to the data file changes, or when the 'Cut Log' control button is pressed. The format for the renamed log file is "name-YYMMDD-hhmm-DX.ext", where YYMMDD is the year, month, and day of month on the host computer, hhmm is the hours and minutes on the host computer, X is the number of days the BDS has been running, and where the original file name was "name.ext"

To pause data collection, click on the "Pause BACnet" checkbox. This will halt all BACnet communication from the BDS until the checkbox is cleared. Also, data will not be written to any data files and no data will be sent to the Coordinator. To halt all data transfer to the Coordinator, but still allow BACnet communication and collect data in the files, click on the "Pause DDE" checkbox.

To end data collection, click on the "Close Window" button. This will also rename the data files as described above.

Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

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Project 2.7 – Enabling Tools

Task 2.7.3 – Development of a BACnet Interface for the Whole-Building Diagnostician (WBD)

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Introduction

The BACnet Data Source (BDS – this is generically referred to as BASBACnet DLL) was developed to be used as a component of the Whole Building Diagnostician (WBD), in conjunction with work on the Virtual Cybernetic Building Testbed (VCBT) (reference 1). The VCBT uses real BACnet enabled mechanical systems and controllers coupled with computer simulations to emulate an entire 3 story building, with three zones per level. Each level has an AHU controller and 3 VAV controllers, with each VAV controller connected to a single zone. The AHU controllers on each level are from three different manufacturers.

The BDS or the BASBACnet provides a data link between the VCBT BACnet controllers/devices and the WBD database (Figure 1). BASLink (Building Automation System Link), a component of the WBD, retrieves data from the VCBT controllers through the BASBACnet and makes the data available to the WBD modules (OAE and WBE) in real-time. After receiving a request from the BASLink process, the BASBACnet retrieves data from the controllers/devices by communicating with them using the native BACnet protocol.

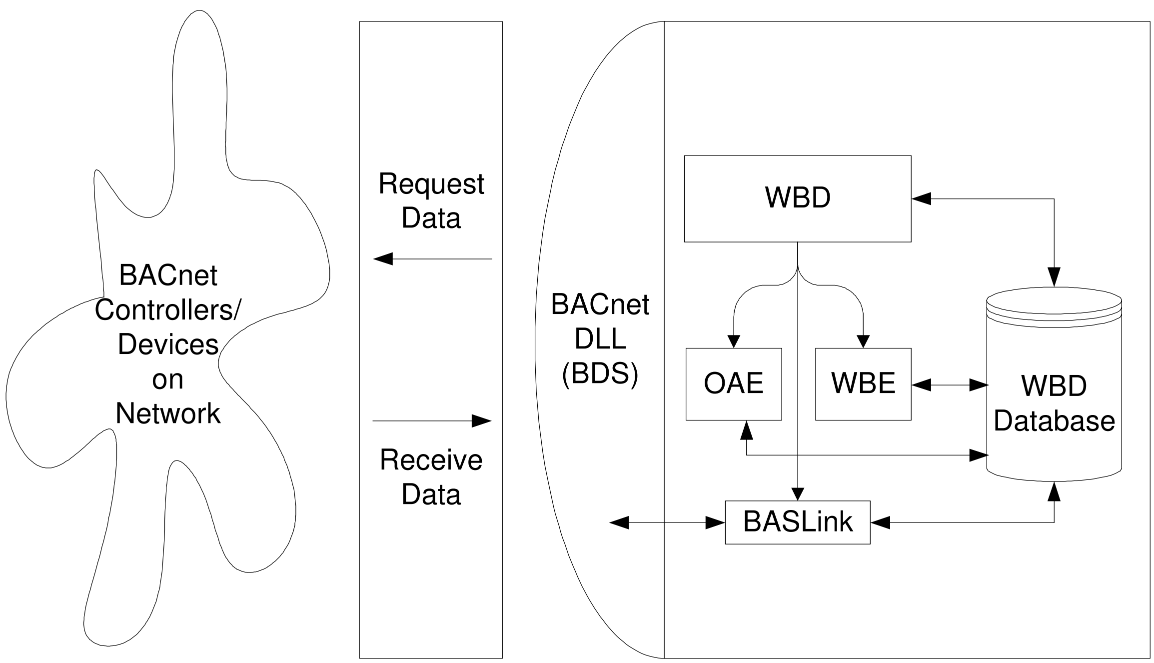

Figure 1 – Overview of the Data Exchange Process

The BASBACnet DLL is capable of retrieving values from BACnet objects on BACnet speaking controllers on an Ethernet network and passing them back to the WBD. While the BDS was developed in conjunction with the VCBT and the WBD, it can be used in any building with a computer connected to a BACnet network[1]. The BASBACnet is capable of retrieving data from multiple controllers on different BACnet subnets, which is an improvement over previous VCBT WBD implementation.

[1] Currently, one of the BACnet support DLLs only runs in a Windows NT 4.0 environment; therefore the data can only be retrieved from by Windows NT 4.0 based computers. The WBD has no such limitations and runs on all Windows operating systems including Windows XP.

Description of the BASBACnet DLL

The BASBACnet DLL is capable of retrieving data from the BACnet speaking controllers/devices connected over an Ethernet network, and returning that data to the WBD database, or any other program that uses it. The BASBACnet DLL can currently handle the following requests for the Present-Value property of Analog Input, Analog Output, Analog Value, Binary Input, Binary Output, and Binary Value objects only.

Configuration

For the BASBACnet to work properly the network information of a BACnet controller or device is required: the BACnet network number, the controller MAC address, and the router MAC address. There are two ways to configure the network information 1) in an initialization file, or 2) with each data point. If all data that are being requested come from a single controller, the network information can be specified in the optional initialization file (wbdlink.ini), as shown in Figure 2. If the requested data spans different controllers that are on different networks (different subnets), then the network information must be associated with each data point.

```
# 1 controller MAC in hex
03

# 2 router MAC in hex, or X if none
0A0B0C0D0E0F

# 3 subnet is in decimal
31
```

Figure 2 – Sample Network Setting File

In addition to the network information of the controllers/devices, a list of data points for which the present value is needed must be listed in the WBD database. Each entry must contain the object type, the object id, and the requested property. The entry may optionally contain network information, which will override the default values for that data point (if an initializing file is specified), as shown in Figure 3. The fields of the entry are:

1. **Device**: The BACnet object instance – this is a required.
2. **Object**: The BACnet object type – this is a required. The possible values for this are: 0 for Analog Input, 1 for Analog Output, 2 for Analog Value, 3 for Binary Input, 4 for Binary Output, or 5 for Binary Value.
3. **Attribute**: The BACnet property (3 or 85 for present-value) – this is a required field.
4. **DMAC**: The MAC address of the controller, in hex – this is an optional field.
5. **RMAC**: The MAC address of the BACnet router, in hex, a value of “X” indicates local network – this is an optional field.
6. **DNET**: The network the controller is on, in decimal, use “0” for local network – this is an optional field.

Sample data entries <u>with</u> an initialization file:
(Device: 1, Object: 0, Attribute: 3) *use default network info for DMAC, RMAC, and DNET*

(Device: 1, Object: 4, Attribute: 3, DMAC: 03, RMAC: 010203040506, DNET: 20) *override default network info for this entry*

(Device: 1, Object: 3, Attribute: 3, DMAC: 05) *override default DMAC, but use default RMAC and DNET*

(Device: 2, Object: 1, Attribute: 3) *uses default network info for DMAC, RMAC, and DNET from settings file*

Sample data entries <u>without</u> an initialization file:
(Device: 1, Object: 0, Attribute: 3, DMAC: 03, RMAC: 0A0B0C0D0E0F, DNET: 20) *set default network info - must be first*

(Device: 2, Object: 2, Attribute: 3) *use default network info for DMAC, RMAC, and DNET set in previous entry*

(Device: 1, Object: 3, Attribute: 3, DMAC: 05) *set new default DMAC, but use previous RMAC and DNET*

(Device: 1, Object: 3, Attribute: 3, DNET: 30) *set new default DNET, but use previous DMAC and RMAC*

(Device: 2, Object: 0, Attribute: 3) *uses DMAC=5, RMAC=0A0B0C0D0E0F, and DNET=30 as set in previous entries*

Figure 3 – Sample Data Entries for Defining the Point Information

If the initialization file is not present, the network information must be present on the first data point entry in the database. That network information is then used as the default, until a data point entry with new network information is read in, after which the latest network information read in will be used as the default.

The entries shown in Figure 3 are entered in the column named **SourceID** within the table named **ChannelConfig** in the WBD database.

Process

The WBD diagnostic modules expect the data from the AHUs and the end-use consumption to be present in the WBD database. Therefore, these data tables have to be populated on a continuous basis using the BASLink component of the WBD. The BASLink module checks the **ChannelConfig** table in the WBD database for a list of data points and passes each data request to the BASBACnet DLL. The BASBACnet takes the request from the BASLink and sends a

BACnet ReadProperty requests to controllers/devices. The data points are uniquely identified using the device and object identification information provided as part of the configuration. The controller/device sends the requested data to the WBD database through the BASBACnet and BASLink modules. The data are continuously read and accumulated in a temporary table. At the end of each hour, the average values are computed and the data moved to relevant tables.

Testing

The BASBACnet DLL was tested using the WBD BASLink Diagnostic module. The BASLink Diagnostic module allows for testing the data collection process without having to configure the database. The relevant configuration information is entered directly in the relevant field as shown in Figure 4.

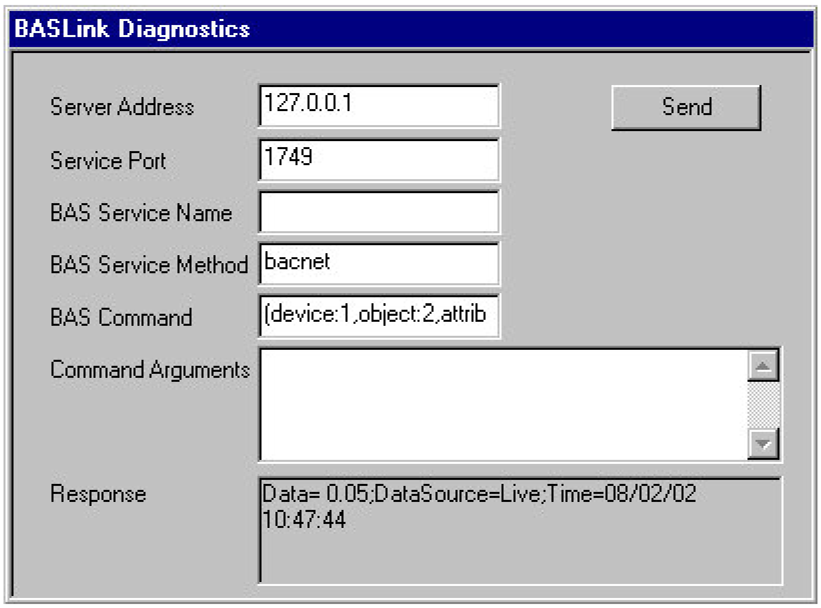

Figure 4 – BASLink Diagnostics Dialog Showing the Configuration Information and the Response from the BACnet Controllers

Future work

The future direction of the distributed version of BASBACnet will depend largely on the needs of the user base. Some anticipated areas for future development are:

1. Increased object/property support
2. Additional connectivity options

An area that is open for improvement is the transfer of data between the WBD and BASBACnet. The BASBACnet is designed to handle multiple requests for data, i.e. it can receive a new data request before previous data requests have been retrieved by the calling program. The WBD currently requires a data request to be returned before sending the next one, which takes more time. Implementing this in the WBD would probably be non-trivial, and is not necessary for the current volume of data, but in the future if increased amounts of data are required this might be a useful change to make.

Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

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Project 2.7 – Enabling Tools

Task 2.7.5 – Results of Testing WBD Features under Controlled Conditions

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Executive Summary

Introduction

This report on Task 2.7.5 – Conduct Blind Test of WBD FDD Capabilities for Project 2.7 – Enabling Tools documents results from testing of the Outdoor-Air Economizer (OAE) and Whole Building Energy (WBE) diagnostic tools. These two diagnostic tools are part of the Whole Building Diagnostician (WBD). The objectives of this project were to test: 1) the automated diagnostic capabilities of the WBD diagnostic modules and 2) the ability of the Virtual Cybernetic Building Testbed (VCBT) to generate test data for both fault free and faulty operating states.

Description of the WBD

The WBD is a production-prototype software package with two modules providing automated diagnostics for air-handling systems and energy use of major building systems (Brambley et al. 1998; and Katipamula et al. 1999). The data for the WBD are generally collected from a direct-digital control (DDC) system employed in the building. The WBD has two diagnostic modules: 1) Outdoor Air Economizer Diagnostician, and 2) Whole Building Energy Diagnostician.

The OAE module diagnoses whether air handlers in a building are supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air when it is appropriate to do so and whether the economizer is wasting energy by supplying excess outdoor air when it should not. Few, if any, sensors other than those used to control most economizers are required, making the tool practical in near-term markets because of its low installed cost.

The OAE diagnostician has five levels of detection sensitivity selectable by users. Increasing the detection sensitivity increases the ability to detect faults and decreases the rate of undetected faults (false negatives), while it also increases the probability of false alarms (i.e., false positives). Properly selecting the sensitivity setting is critical to achieve the desired balance between these factors. Because of differences in equipment among buildings and differences in preferences among users, each user can empirically adjust the sensitivity level to obtain the desired OAE performance.

The OAE alerts users to the presence of faults with results provided for each hour. Because of uncertainty in measurements and changing indoor and outdoor conditions, a given fault may or may not manifest continuously (during consecutive hours). In some cases, the fault may appear for a few hours and then may not appear again for several weeks or months. As a result, it is recommended that users ignore sporadic indications of operation problems and instead wait for the appearance of several sequential fault indicators or fault indicators occurring in a repetitive pattern over time (e.g., at 1 p.m. on every week day). In general, the ability and experience of the user plays a significant role in how the diagnostic tool is used.

The WBE module monitors variations in energy use at the whole-building or subsystem levels. It does this by tracking actual energy consumption and comparing it to estimated expected consumption, which is provided by an empirical model that uses up to five independent variables including time of day, day of week, and weather conditions. The WBE automatically constructs the baseline model for estimating expected consumption using historical energy consumption data from the system being tracked and values for the relevant independent variables specified by the user. Using this baseline model, the WBE alerts the user when the actual measured consumption deviates significantly from the estimated expected consumption. The tool requires up to 9 months of data to build a model adequate for predicting an entire year of operation; however, useful results become available with about 6 weeks of data.

Both tools provide information to users in simple, graphical displays that indicate the presence or absence of faults at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the fault detected.

Description of the VCBT and Simulation Environments

The VCBT is an emulation environment that combines simulations of a building and its heating, ventilation, and air-conditioning (HVAC) system with actual commercial controllers. It provides a way to conduct tests under a wide variety of controlled conditions and to compare the results of several different commercial products. Details of the VCBT design and operation are documented by Bushby et al. (2001). Emulation provides a test environment that is closer to a real building because it uses real building controllers. Like simulation, it also provides controlled and reproducible conditions. Because emulation is done in real time, it takes much longer than simulation, making it more difficult to test a broad range of faults and conditions in a limited time. The VCBT was used to generate data to test the OAE module. For this study, the VCBT was configured with one AHU for each of three floors, designated AHU-1, AHU-2, and AHU-3. AHU-1 and AHU-3 are variable air volume (VAV) systems, each with three VAV boxes. AHU-2 is a constant volume system, with three zone reheat coils.

As reported earlier, the WBE module requires 9 months of training data, as well as several days of data for each fault; the use of the VCBT (which runs in real time) as a testing environment was not possible. Instead, a pure computer simulation based on HVACSIM$^+$ (Park et al. 1986) and similar to the HVAC system and building shell simulation components of the VCBT was used. The model simulates one floor of an office building and its associated mechanical equipment. A single duct AHU supplies air to three zones. Each zone is served by a VAV terminal box. The AHU sensors, dampers, valves, coils, actuators, ducts, and fans, and the VAV box sensors, dampers, coils, and valves are represented by HVACSIM$^+$ component models. Most of the component models used were originally developed for an ASHRAE research project and documented by Haves and Norford (1997). For this study, the model was expanded to three floors, each of which is provided with an AHU and three VAV boxes. In addition, chiller and boiler component models were added to compute electricity and gas energy consumption data for the WBE module.

Testing Process

Similar testing processes were used for both the OAE and WBE modules. The ability of these modules to detect and diagnose faults was tested as follows:

1. Specify system, controls and data requirements for the OAE module and the data requirements for the WBE module and list the potential faults that each module can detect.

2. Modify the VCBT and the $HVACSIM^+$ simulation to conform to the requirements.

3. Configure the WBD for the systems and controls selected.

4. Generate “clean” fault-free data.

5. Validate the “clean” data using the WBD and build baseline models for the WBE module.

6. Generate fault data for the selected systems for non-blind verification of data and the WBD.

7. Validate the WBD with the known fault data .

8. Generate fault data for the selected systems for blind tests of the WBD: 15 blind-test data sets for testing the OAE diagnostician and 4 data sets for blind testing the WBE diagnostician. The data sets for blind tests were developed by NIST without consultation with Battelle Staff.

9. Process the blind fault data with the WBD (by Battelle staff).

10. Evaluate the results of the blind tests.

Results

The performance of the OAE diagnostician in the blind tests is presented in Table ES1. Results are presented for low, normal, and high sensitivity. Using the OAE at its low sensitivity setting, 8 of the 15 faults were correctly identified, no false positives were obtained, and 7 faults were not detected (false negatives). For the normal sensitivity setting, 11 of the 15 faults were correctly detected, no false positives were reported, and 4 faults were not detected. With the high sensitivity setting, 10 of the 15 faults were correctly identified, 2 false positives were reported, and 3 faults were not detected (false negatives). In each of the three cases, two of the false negatives were due to the conditions masking the faults so that even though the fault existed in the model, conditions were not appropriate for conditions (e.g., temperatures) to be affected by the presence of the faults.

The performance of the WBE diagnostician is presented in Table ES2. In three of the four blind trials, the WBE correctly identified anomalous energy use caused by a fault; with the single false negative (undetected problem) due to the small magnitude of the fault (this fault had an energy impact below the WBE reporting threshold of $1/day).

Conclusions

Overall, both the OAE and WBE modules of the WBD performed quite well. The best performance of the OAE module was obtained with normal sensitivity, which is the normally recommend setting. More research is needed to provide specific guidance to users regarding 1) how to select the appropriate sensitivity settings and 2) how to interpret the results of the WBD.

The VCBT emulation and the HVACSIM$^+$ simulation were successful in generating data representing normal and faulty operations and provided data useful for testing automated diagnostic tools. Further use of these environments to complement field testing of FDD tools is justified.

Table ES1 - Summary of Results for the OAE Module (SAT = supply-air temperature, MAT = mixed-air temperature, RAT – return-air temperature, OA = outdoor air, OAT = outdoor-air temperature)

	Sensitivity = Low		Sensitivity = Normal		Sensitivity = High	
Fault Instigated in VCBT	OAE Result (Fault / No fault)	OAE Correct?	OAE Result (Fault / No fault)	OAE Correct?	OAE Result (Fault / No fault)	OAE Correct?
SAT sensor drift	No fault	False negative	No fault	False negative	No fault	False negative
Fault Free	No fault	Correct	No fault	Correct	No fault	Correct
MAT sensor failure	Fault	Correct	Fault	Correct	Fault	Correct
Recirculation damper leakage	Fault	Correct	Fault	Correct	Fault	Correct
Fault free	No fault	Correct	No fault	Correct	Fault	False positive
RAT sensor drift	No fault	False negative[1]	No fault	False negative[1]	No fault	False negative[1]
OAT sensor failure	Fault	Correct	Fault	Correct	Fault	Correct
RAT sensor drift	No fault	False negative[1]	No fault	False negative[1]	No fault	False negative[1]
OA damper stuck at minimum	No fault	False negative	Fault	Correct	Fault	Correct
MAT sensor drift	Fault	Correct	Fault	Correct	Fault	Correct
Fault free	No fault	Correct	No fault	Correct	Fault	False positive
Recirculation damper leakage	No fault	False negative	Fault	Correct	Fault	Correct
SAT sensor failure	No fault	False negative	No fault	False negative	Fault	Correct
Economizer control logic fault	Fault	Correct	Fault	Correct	Fault	Correct
RAT sensor drift	No fault	False negative	Fault	Correct	Fault	Correct

[1] The presence of the fault was masked by the conditions.

Table ES2 - Summary of Results for the WBE module.

Fault Instigated in Simulation	WBE Result (Fault / No Fault)	Correct?
10% increase in HVAC electricity consumption	No fault	False negative[1]
15% increase in boiler gas consumption	Fault	Correct
Scheduling problem – same internal loads weekdays and weekends	Fault	Correct
Progressively developing increase in chiller electrical energy consumption	Fault	Correct

[1] The false negative was due to the small magnitude of the fault (faults resulting in impacts of less than $1/day are below the WBE reporting threshold.

1 Introduction

The last decade has seen a tremendous growth and interest in the development of methodologies to detect and to diagnose performance degradation and faults in building systems (Katipamula et al. 2000). However, only a few fault detection and diagnostic (FDD) systems developed actually have been deployed in the field. Most of the development, testing and prototyping of FDD systems, with a few exceptions, has been limited to work in research laboratories and universities.

The Whole Building Diagnostician (WBD) has been one notable exception to this. It has been tested at a number of sites throughout the western U.S. In Project 2.4 of this program, it is currently being tested in three use scenarios: 1) use by the operation staff of a single, large, office building; 2) use by the staff managing a collection of office buildings; and 3) use by a heating ventilation and air-conditioning (HVAC) service provider. These field tests have been useful to verify the success of the WBD in detecting actual building operation problems and to demonstrate the value of the WBD, but because many uncontrolled variables exist in real operation, they do not provide controlled tests of the WBD. This project is intended to provide testing of the WBD under controlled conditions, while also providing an opportunity to demonstrate the value of the National Institute for Standards and Technology's (NIST's) Virtual Cybernetic Building Testbed (VCBT) and fault detection and diagnostics (FDD) test shell in testing automated diagnostic tools like the WBD.

The objectives of this project were to test: 1) the automated diagnostic capabilities of WBD diagnostic modules and 2) the ability of the VCBT and FDD test shell to generate test data for both fault free and faulty operating states. In this report, the results for testing of the WBD modules on data corresponding to faulty operation are presented. The data were generated under controlled conditions at NIST.

The WBD is a production-prototype software package with two modules providing automated diagnostics for air-handling systems and energy use of major building systems (Brambley et al. 1998; and Katipamula et al. 1999). The data for the WBD are generally collected from a direct-digital control (DDC) system employed in the building. The WBD has two diagnostic modules: 1) Outdoor Air Economizer diagnostician (OAE), and 2) Whole Building Energy Diagnostician (WBE).

The OAE module diagnoses whether air handlers in a building are supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air whenever it is appropriate to do so and not wasting energy by supplying excess outdoor air when it should not. Few, if any, sensors other than those used to control most economizers are required, making the tool practical in near-term markets because of its low installed cost.

The WBE module monitors variations in energy use at the whole-building or subsystem levels. It does this by tracking actual consumption and comparing it to estimated expected consumption, which is modeled as a function of up to five independent variables including time of day, day of week, and weather conditions. The WBE automatically constructs a baseline model for estimating expected consumption using historical energy consumption data from the system being tracked and values for the relevant independent variables specified by the user. Using this baseline model, the WBE alerts the user when the actual measured consumption deviates significantly from the estimated expected consumption. The tool requires up to 9 months of data to build a model adequate to predict an entire year of operation; however, useful results become available with about 6 weeks of data.

Both tools provide information to users in simple, graphical displays that indicate the presence or absence of faults at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the faults detected.

This document provides a summary and background on the WBD and its modules, a brief description of the plan for testing, the evaluation process and the results for the blind tests. In Section 2, the various steps in the testing process are outlined, followed by Section 3, which provides a description of the evaluation process, followed by the WBD test plan in Section 4. The data generation process in the VCBT environment is described in Section 5. The results from blind tests of the OAE on data for air-handling units (AHUs) are provided in Section 6, followed by the results from blind tests of the WBE in Section 7. The results from the diagnostic modules are summarized and compared with actual faults instigated by NIST in Section 8. The conclusions and recommendations are provided in Section 9, and a list of references is provided in Section 10.

2 Testing Process

The process that was used to test the diagnostic capabilities of the two WBD modules (OAE and WBE) was:

1. Battelle specified the capabilities of the WBD diagnostic modules and provided NIST with lists of possible faults for the two modules.

2. NIST made the necessary modifications to the VCBT simulation engine and the HVACSIM$^+$ (Park et al. 1986) simulation models (the latter used to generate data for the WBE module) to generate fault-free data.

3. Battelle validated the fault-free data for AHUs from NIST by processing it with the OAE module. This ensured that the OAE showed that the data being generated was as specified and that the OAE module was properly configured with the type of controls being used in the VCBT and the sensor accuracies and thresholds properly specified.

4. NIST also generated 12 months of fault-free end-use data for training the WBE module. A reference model for each end-use being monitored was built using this fault-free training data.

5. NIST then generated three data sets with known faults for non-blind tests of the OAE module. The data sets spanned periods of 1 week. These data sets were used to further calibrate the OAE configuration parameters and to ensure that the OAE was properly configured to distinguish the faults. This process also validated the ability of the VCBT to generate data for faulty operation as specified.

6. NIST also generated end-use consumption data corresponding to known faults. This data was then used for non-blind tests of the WBE module.

7. NIST then generated data corresponding to faulty operations for the two WBD modules. The faults were selected by NIST and were unknown to Battelle so that testing would be blind.

8. The data sets for faulty operations were automatically processed by Battelle using the two diagnostic modules with no knowledge of what faults, if any, were represented in the data sets, and results were sent to NIST for evaluation.

3 Evaluation Process

The evaluation process used to test the automated diagnostic capabilities of the two WBD modules is described in this section. The data sets representing faulty operations were generated by NIST using the VCBT/FDD test shell. These data sets were processed in an automated way similar to how a building operator or a building manager would use the tool. In addition to the automated processing, the data from AHUs were also processed using semi-automated graphical routines outside the WBD that were developed for advanced users. These graphical routines provide additional details not provided directly by the WBD.[1] The various steps of the evaluation process are:

1. First, the "faulty" data sets were processed with the WBE and OAE modules.

2. Selected AHU data sets were processed using semi-automated graphical routines.

3. The results from automated and semi-automated analysis were summarized, tabulated, and reported to NIST.

4. NIST compared the faults identified by the WBE and the OAE to the faults actually introduced.

5. If the identified faults did not match the actual, the cause of the difference was identified jointly by NIST and Battelle.

6. Finally, the ability of the two modules to detect the faults was summarized by Battelle.

[1] They also represent additional diagnostics, which could be added to the tools in the future.

4 WBD Test Plan

This section specifies how the team planned to verify the data from the VCBT and describes the general requirements for the test data and limitations of the two diagnostic modules.

4.1 VCBT Validation Plan

One of the primary objectives of this work was to verify the capability of VCBT to generate both fault-free data and data from faulty operations. Therefore, before the OAE and the WBE modules process the simulated data from faulty operations, the data from the VCBT and the simulation models (for WBE) must be verified and validated. To a large extent, the validation can be accomplished by using graphical tools to view the raw data from the VCBT and the simulation models.

4.1.1 VCBT Validation Process

The process to test the ability of the VCBT to generate fault-free data and data corresponding to faulty operations was:

1. Specify system, controls and data requirements for the OAE (Battelle).

2. List the faults that the OAE can detect and diagnose (Battelle).

3. Modify the VCBT as needed to provide the measured data required for the OAE module (NIST).

4. Modify the VCBT to emulate one AHU with a constant air-volume system (NIST).

5. Pick one or more economizer-control strategies (NIST).

6. Generate "clean" fault-free data for the selected AHUs and economizer-control strategies. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling) (NIST).

7. Validate the "clean" data using the WBD and the OAE modules (Battelle).

8. Pick a list of faults that will be used in the blind tests (NIST).

9. Modify the VCBT to provide data corresponding to faulty operation (NIST).

10. Generate data with faulty operations for the selected systems (NIST).

11. Validate the raw data from faulty operations through the use of graphical tools (NIST and Battelle).

4.2 OAE Plan

To detect and diagnose the faults with ventilation and economizer operations of an AHU, all data listed in the data requirements section are needed. In addition, the OAE must be properly configured to identify the type of AHU and the type of economizer controls employed.

4.2.1 Selection of Systems

As mentioned earlier, the OAE module is capable of detecting and diagnosing faults with constant-air volume (CAV) systems and variable-air volume (VAV) systems that do not meter the outdoor-air-flow rate (i.e., the intake). Therefore, for the blind tests, NIST selected three air-handling systems with one being a CAV system, and the other two VAV systems. The OAE has been designed primarily to detect and diagnose faults with constant-volume built-up systems and constant-volume packaged roof-top units. If a VAV system is selected, the outdoor-air flow must be ensured to float with the supply-air flow rate (i.e., the outdoor-air flow is not metered).

4.2.2 Selection of Economizer Controls

Again, as mentioned earlier, the OAE module can detect faults with almost all commonly found economizer-control strategies, such as, high-limit (dry-bulb temperature or enthalpy), or differential (dry-bulb temperature or enthalpy). For the test, NIST picked one air handler with high-limit dry-bulb-temperature control, and the other two systems with differential enthalpy economizer control strategies.

4.2.3 Generation of Fault-Free Data for the OAE Module

First, NIST generated “clean” fault-free data for all AHUs selected. The data was to preferably span all operating modes (heating, cooling, economizing only, economizing and cooling). The “clean” data without faults was processed using the OAE; this enabled verification of the configuration parameters, the dead bands, the sensitivities set in the OAE, and enabled ensuring that the data from the VCBT/FDD test shell was as expected. Once the “clean” data from the AHUs was validated using the OAE, the OAE was ready to accept the faulty data for the blind tests.

4.2.4 Generation of Faulty Data for the OAE Module

The OAE module can detect and diagnose a number of faults with ventilation and economizer operations of an AHU. Because blind tests with a number of different faults were created for testing the OAE’s detection and diagnostic capabilities, the data from the blind tests were stored in separate databases, each database representing a single (fault-free or faulty) blind test. As mentioned earlier, some faults take several hours, days and sometimes even months to manifest themselves. Therefore, faulty operation was to persist for the entire period of data collection for each blind test. The length of faulty operation was to be sufficiently long for the fault to manifest.

If an AHU has simultaneous multiple faults (i.e., more than one fault at a time), the OAE module will detect a problem, but may not be able to diagnose the causes of more than one fault simultaneously. Therefore, it was preferable not to have simultaneous multiple faults for the majority of the blind tests; this limitation was already known.

4.2.5 OAE Testing Process

The ability of the OAE to detect and diagnose faults was tested as follows:

11. Specify system, controls and data requirements for the OAE (Battelle).
12. List the potential faults that the OAE can detect and diagnose (Battelle).
13. Modify the VCBT to provide the measured data required for the OAE module (NIST).
14. Implement modifications to the VCBT so that one of the AHUs emulated is a CAV system (NIST).
15. Pick one or more economizer control strategies (preferably one of them based on high-limit dry-bulb temperature) (NIST).
16. Configure the WBD for the systems and controls selected (Battelle).
17. Generate "clean" fault-free data for the selected AHUs and economizer-control strategies. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling) (NIST).
18. Validate the "clean" data using the WBD and the OAE modules (Battelle).
19. Pick a list of faults to be used in the blind test (NIST).
20. Modify the VCBT to provide the "faulty data" (NIST).
21. Generate fault data for the selected systems (NIST).
22. Process the fault data with the OAE (Battelle).

~~13.~~23. Evaluate the results (Battelle/NIST).

4.3 WBE Test Plan

Unlike the OAE module, the WBE operates independently of the details of the building systems and control strategies. The WBE can detect abnormal energy end-use consumption cause by improper or faulty operations, and more than one fault can cause the abnormal energy consumption. The current version of the WBE is limited to monitoring four end-uses at a time. As the VCBT is an emulator, it generates data in real time. Given this limitation, it would take a significant amount of time for the VCBT to generate the necessary training data (6 to 9 months) for the WBE. Therefore, it was decided that the test data (both training and "faulty data") would be generated using an HVACSIM$^+$ simulation (based on the simulation models used in the VCBT without the emulation elements).

4.3.1 Generation of Fault-Free Data for the WBE Module

First, NIST generated "clean" fault-free data for all energy end-uses selected. The data covered 12 months, so that it spanned all operating modes (heating, cooling, economizing only, and economizing with cooling). The "clean" data without faults was processed using the WBE; this enabled verification of the configuration parameters and the sensitivity settings of the WBE, and also ensured that the data from the simulation models were as expected. In addition, the "clean" data was used by the WBE to empirically develop the baseline reference models. Once the fault-free data for each end-use was validated and baseline models developed, the WBE was ready to accept "faulty data" for the blind tests.

4.3.2 Generation of Data for Faulty Operation for the WBE Tests

The WBE module can detect a number of faults with energy end-uses. Unlike the blind test data for the OAE module, all data for blind tests of the WBE were stored in a single database, because the reference models were common to all faults.

As mentioned earlier, the WBE processes hourly data, but generates the Energy Consumption Indexes (ECIs) at daily intervals. Therefore, unless the faults or deviations in the energy consumption occur over several hours within a day, the WBE may not detect them (depending on the magnitude of the energy impacts of those faults and the sensitivity setting of the WBE). A fault with gradual degradation in performance or gradual increase or decrease in energy end-use was created.

4.3.3 WBE Testing Process

The process to test the ability of the simulation models to generate fault-free data and "faulty data" and the ability of the WBE to detect faults was accomplished as follows:

1. Specify data requirements for the WBE (Battelle).

2. List the potential faults the WBE can detect (Battelle).

3. Modify the HVACSIM$^+$ simulation to provide the measured data required for the WBE module (NIST).

4. Configure the WBD to the systems selected (Battelle).

5. Generate twelve months of "clean" fault-free data for the selected end-uses. Preferably, the data was to span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling).

6. Validate the "clean" data using the WBD and also build baseline models for the selected end-uses (Battelle).

7. Pick a list of faults that will be used in the blind tests (NIST).

8. Modify the simulation to provide the data corresponding to faulty behavior (NIST).

9. Generate data with faulty operation for the selected end-uses (NIST).
10. Process the data for faulty operation with the WBE (Battelle).
11. Evaluate the results (Battelle/NIST).

5 Data Generation

5.1 Data Generation for the OAE Module

The Virtual Cybernetic Building Testbed (VCBT) is an emulation environment that combines simulations of a building and its HVAC system with the actual commercial controllers. It provides a way to conduct tests under a wide variety of carefully controlled conditions and to compare the results of several different commercial products. Details of the VCBT design and operation are documented by Bushby et al. (2001). Emulation provides a test environment that is closer to a real building because it uses real building controllers but, like simulation, it also provides carefully controlled and reproducible conditions. Because emulation is done in real time, it takes much longer than simulation, making it more difficult to test a broad range of faults and conditions in a limited time.

For this study, the VCBT was configured with one AHU for each of the three floors, designated AHU-1, AHU-2, and AHU-3. AHU-1 and AHU-3 are VAV systems, each with three VAV boxes. AHU-2 is a constant volume system, with three zone reheat coils.

5.2 Control Strategies AHU-1

5.2.1 Fan Control

The supply-air fan speed is controlled to maintain the supply-air pressure at a fixed supply-air pressure set point. The return-air fan speed is controlled to maintain a constant difference between the supply- and return-air flow rates.

5.2.2 Temperature Control

AHU-1 uses a single proportional integral (PI) control loop to determine a temperature control signal to maintain the supply-air temperature at a fixed supply-air temperature set point. Depending on the magnitude of the signal, it is mapped to one of three outputs, which control the heating coil, cooling coil, or mixing-box dampers. Logical interlocks set the position of the other two outputs appropriately depending on which one is active. For example, if the heating coil valve is active, the cooling coil valve will be fully closed and the mixing-box damper will be set to the minimum position (which depends on the occupancy status). The outdoor-air and the return-air enthalpies are compared to determine whether to enable or disable economizer operation.

5.3 Control Strategies AHU-2

5.3.1 Fan Control

AHU-2 is a constant volume system, so the supply-air fan and return-air fan both operate at fixed speeds.

5.3.2 Temperature Control

AHU-2 uses a single PI control loop to determine a temperature control signal to maintain the supply-air temperature at a fixed supply-air temperature set point. Depending on the magnitude of the signal, it is mapped to one of three outputs, which control the heating coil, cooling coil, or mixing-box dampers. Logical interlocks set the position of the other two outputs appropriately depending on which one is active. For example, if the heating coil valve is active, the cooling coil valve will be fully closed and the mixing-box damper will be set to the minimum position (which depends on the occupancy status). The outdoor-air temperature is compared to a fixed changeover temperature to determine whether to enable or disable economizer operation.

5.4 Control Strategies AHU -3

5.4.1 Fan Control

The supply-air fan speed is controlled to maintain the supply-air pressure at a fixed supply-air pressure set point. The return-air fan speed is controlled to maintain a constant difference between the supply-air and return-air flow rates.

5.4.2 Temperature Control

AHU-3 uses a separate PI control loop for each of three outputs which control the supply-air temperature: the heating coil, cooling coil, and mixing-box dampers. The heating coil and cooling coil outputs are controlled to maintain supply-air temperature at a fixed supply-air temperature set point. The mixing box dampers are controlled by comparing the outside-air and the return-air enthalpies. If the return-air enthalpy is greater than the outdoor-air enthalpy, the mixing-box damper control loop maintains mixed-air temperature at its set point (also fixed). Interlocks, dead bands, and time delays are incorporated to prevent undesirable simultaneous heating, cooling, and economizing.

5.5 Normal Operation

Data from a 3-week fault-free emulation using swing season (October) weather data are presented to highlight normal operation.

Figure 1 and show temperature and control signal data, respectively from AHU-2 on day 4 of the 21-day emulation. During the early part of the day, the outdoor-air temperature (green, Figure 1) is low, as is the outdoor-air enthalpy (not shown). At this time, the economizer (green, Figure 2) is fully open, bringing in 100 % outdoor air. As the day progresses, the outdoor-air temperature and enthalpy increase, so that at some point the condition is no longer favorable for economizing. When this happens, the economizer goes from fully open to 20 % open (the minimum position for ventilation). Throughout the day, the cooling coil (blue, Figure 3) modulates to maintain the supply-air temperature (light blue, Figure 1) at the supply-air temperature set point (dark blue, Figure 1).

Figure 3 show temperature and control signal data, respectively, from AHU-2 on day 8 of the 21 day emulation. During the early part of the day, the outdoor-air temperature (green, Figure 3) is low, as is the outdoor-air enthalpy (not shown). At this time, the economizer (green, Figure 4) modulates to maintain the supply-air temperature (light blue, Figure 3) at the supply-air temperature set point (dark blue, Figure 3). As the day progresses, the outdoor-air temperature and enthalpy increase, so that the economizer must open further and further to maintain the supply-air temperature at the set point. At some point, the economizer saturates at the fully open position, and the cooling coil (blue, Figure 4) opens and modulates to maintain the supply-air temperature at the set point.

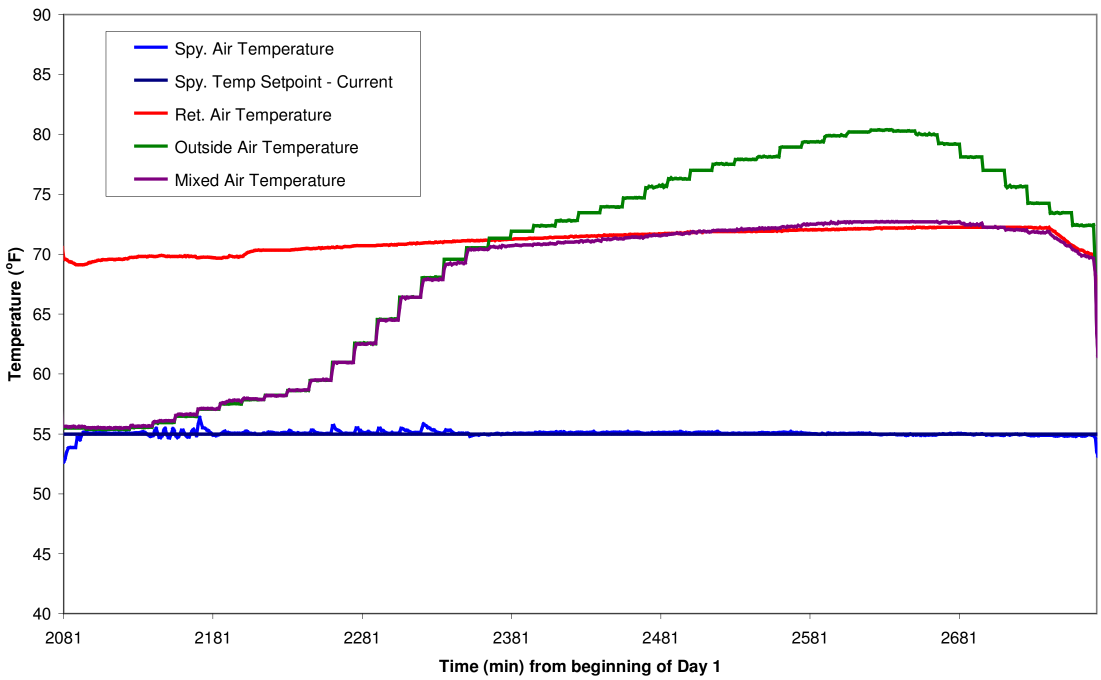


Figure 1 – VCBT AHU-2 Temperatures Representing Normal Operations (Swing Season Day 4)

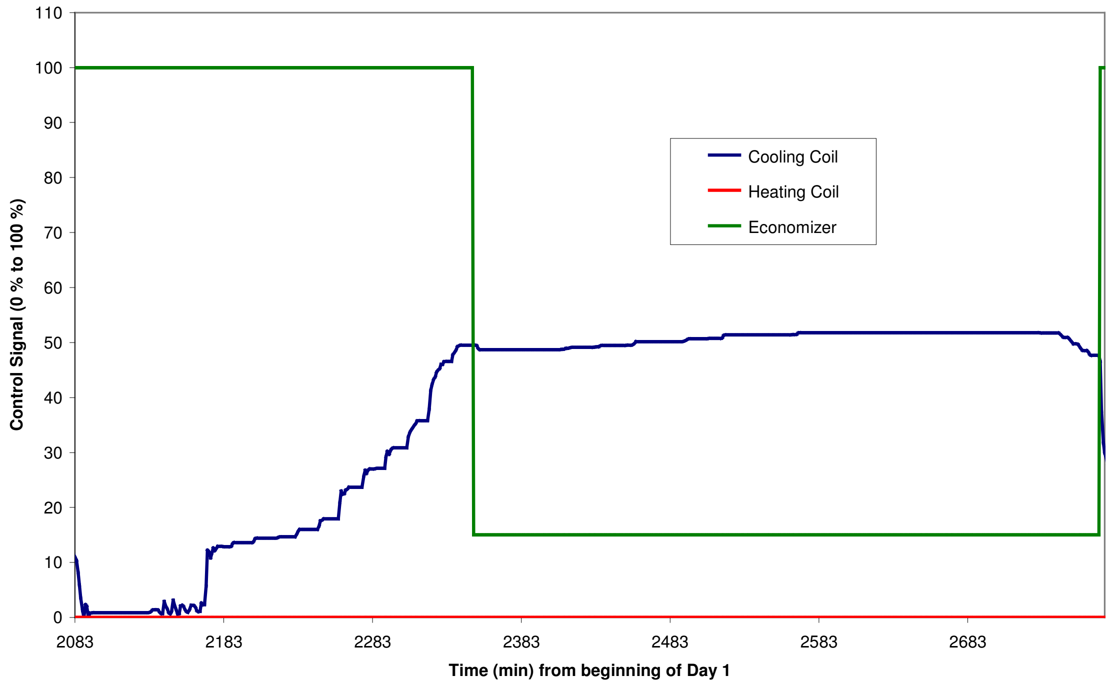


Figure 2 – VCBT AHU-2 Control Signals Representing Normal Operations (Swing Season Day 4)

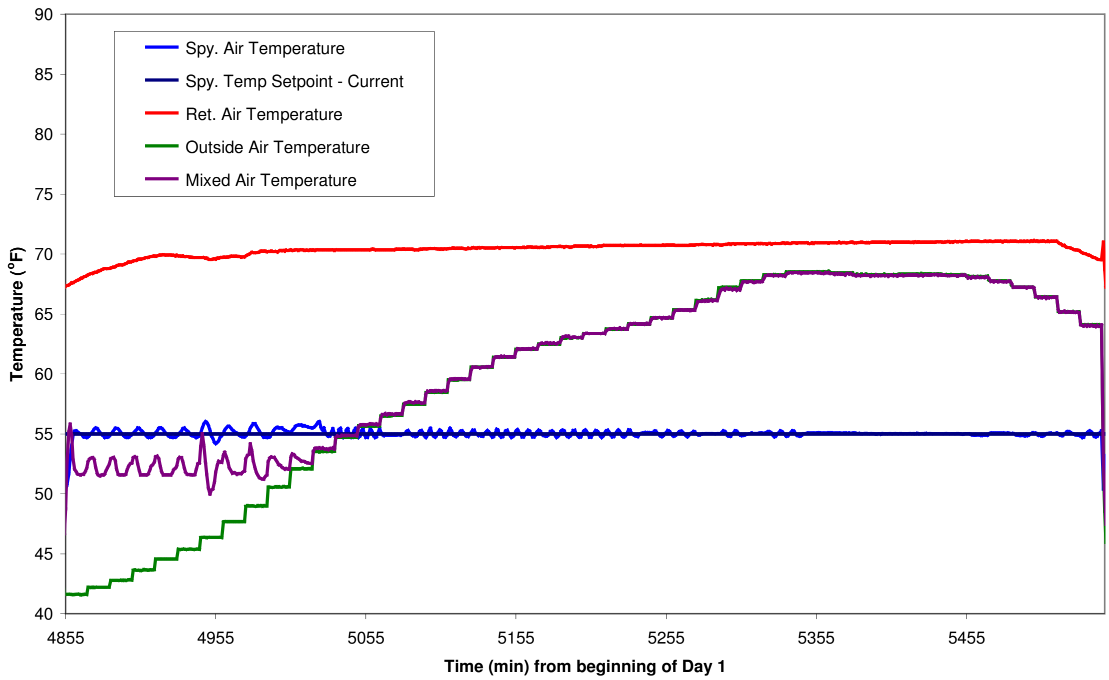


Figure 3 – VCBT AHU-2 Temperatures Representing Normal Operations (Swing Season Day 8)

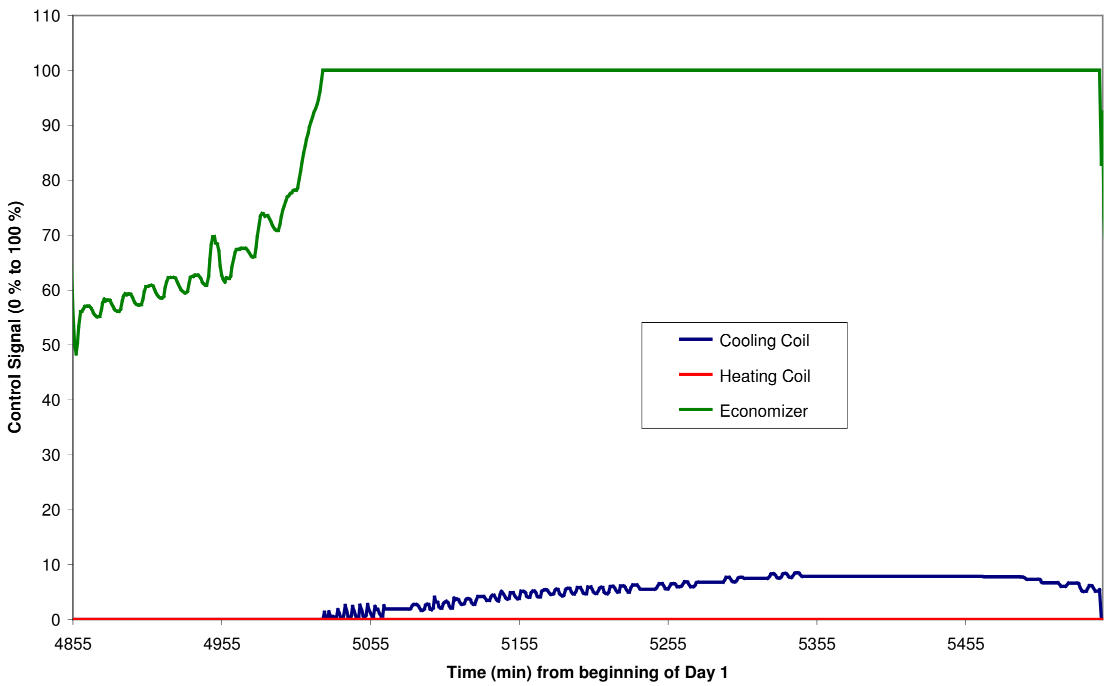


Figure 4 – VCBT AHU-2 Control Signal Representing Normal Operation (Swing Season Day 8)

5.6 Faulty Operation

The following faults were included in the blind tests of the OAE module.

5.6.1 Supply Air Temperature Sensor Drift

This fault is introduced as a sensor offset beginning at 0 ºF and increasing linearly over a three week emulation period to +7 ºF. The positive sensor drift means that the measured supply-air temperature is greater than the actual supply-air temperature by the amount of the offset.

Figure 5 and Figure 6 show AHU-1 data from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 5) and humidity (not shown) are low enough to permit economizing, so the mixing box dampers (green, Figure 6) are modulated to maintain the supply-air temperature (light blue, Figure 5) at its set point (dark blue, Figure 5). The effects of this fault are easily observed on this day, as the cooling coil (blue, Figure 6) and heating coil (red, Figure 6) are closed. Under these conditions, the supply and mixed-air temperatures should be equal (with a small difference caused by the temperature rise across the supply fan), but in fact the supply-air temperature (light blue, Figure 5) is nearly 4 ^{o}C less than the mixed-air temperature (purple, Figure 5). Because the AHU controller maintains the supply-air temperature at the supply-air temperature set point (dark blue, Figure 5), the fault causes an increase in actual supply-air temperature.

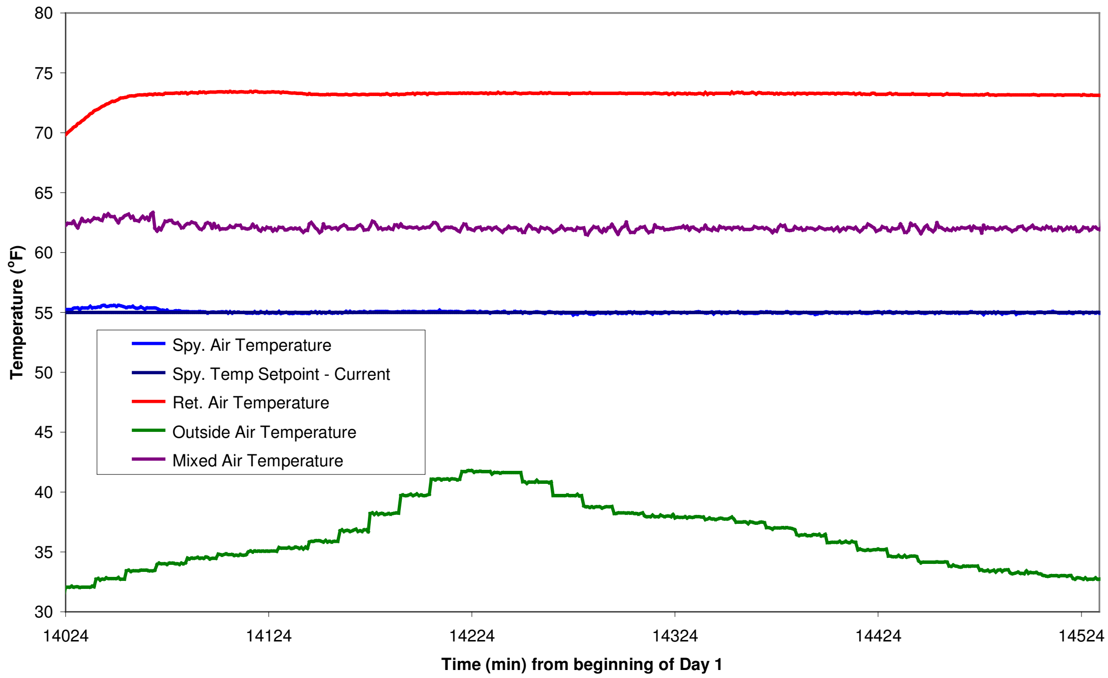


Figure 5 – VCBT AHU-1 Temperatures for Supply-Air Temperature Sensor Drift Fault (Heating Season Day 21)

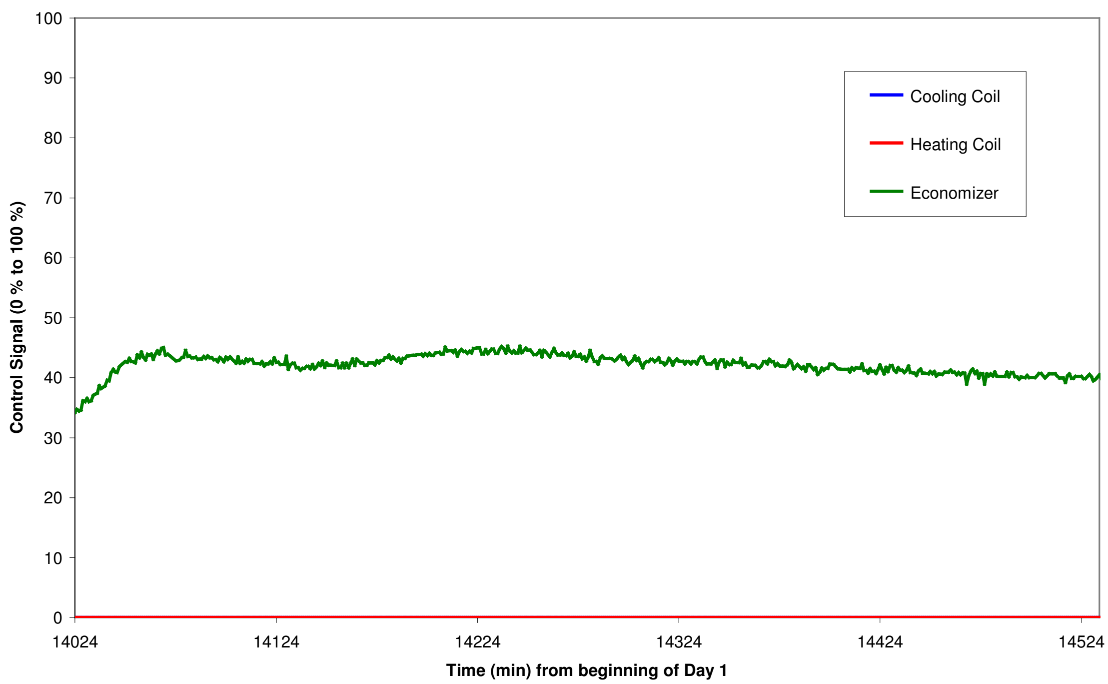


Figure 6 – VCBT AHU-1 Control Signals for Supply-Air Temperature Sensor Drift Fault (Heating Season Day 21)

5.6.2 Mixed-Air Temperature Sensor Drift

This fault is introduced as a sensor offset beginning at 0 ºF and increasing linearly over a 3 week emulation period to +7 ºF. The positive sensor drift means that the measured mixed-air temperature is greater than the actual mixed-air temperature by the amount of the offset.

Figure 7 and Figure 8 show AHU-3 data from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 7) and humidity (not shown) are high enough to prohibit economizing, so the mixing-box dampers (green, Figure 8) are aligned to bring in the minimum amount of outdoor-air needed for ventilation. The actual mixed-air temperature is between the return-air and outdoor-air temperatures, because it is the result of blending the outdoor-air and return-air streams. However, because of the sensor drift, the measured mixed-air temperature is below the return-air temperature by approximately 5.4 °F.

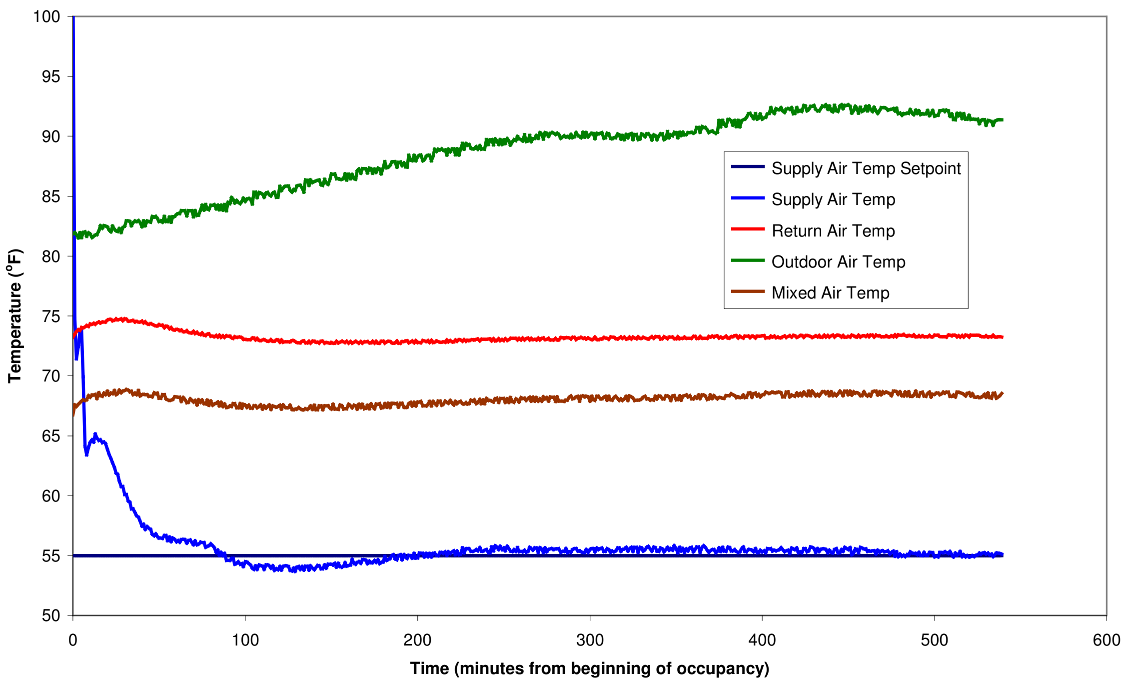


Figure 7 – VCBT AHU-3 Temperatures for Mixed-Air Temperature Sensor Drift Fault (Cooling Season Data)

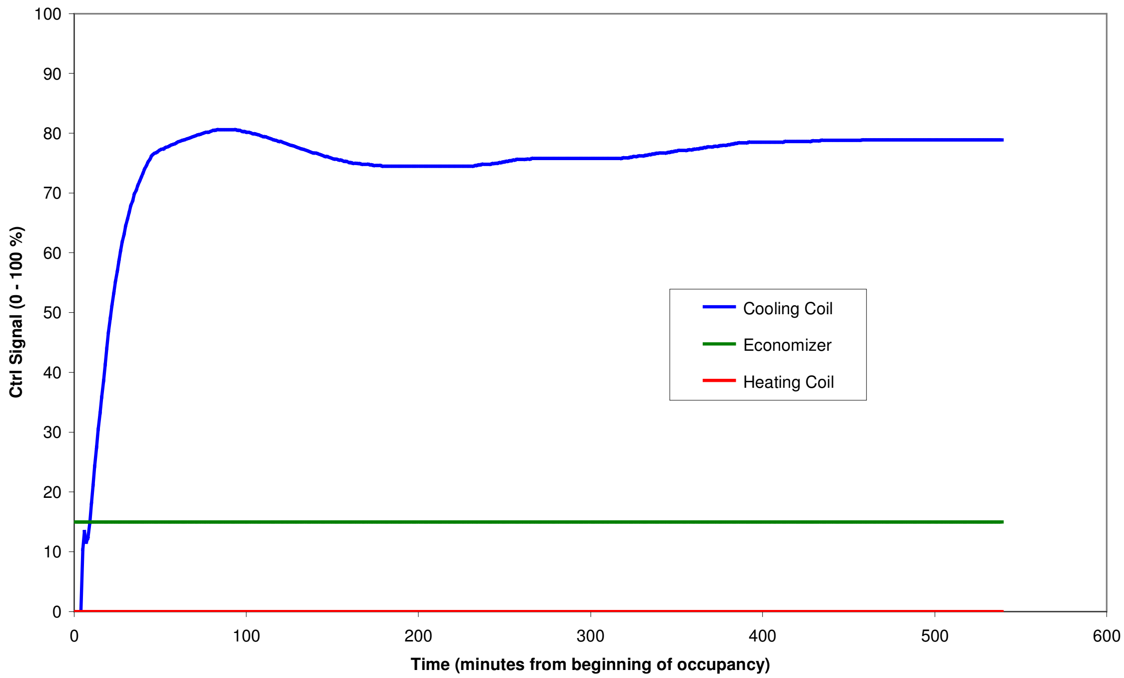


Figure 8 – VCBT AHU-3 Control Signals for Mixed-Air Temperature Sensor Drift Fault (Cooling Season Data)

5.6.3 Return Air Temperature Sensor Drift

This fault is introduced as a sensor offset beginning at 0 ºF and increasing linearly over a 3 week emulation period to +7 ºF. The positive sensor drift means that the measured return-air temperature is greater than the actual return-air temperature by the amount of the offset.

Figure 9 and Figure 10 show AHU-3 data from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 9) and humidity (not shown) are high enough to prohibit economizing, so the mixing-box dampers (green, Figure 10) are aligned to bring in the minimum amount of outdoor air needed for ventilation. The mixed-air temperature is between the actual return-air and outdoor-air temperatures, because it is the result of blending the outdoor-air and return-air streams. However, because of the sensor drift, the mixed-air temperature is below the measured return-air temperature by approximately 5.8 °F.

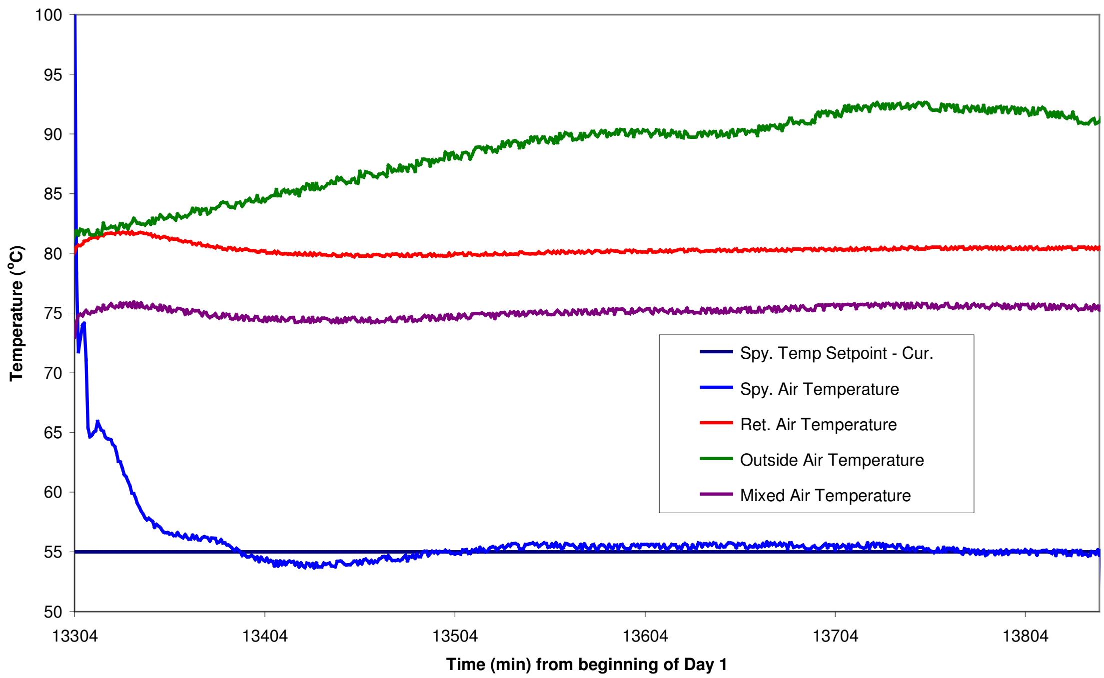


Figure 9 – VCBT AHU-3 Temperatures for Return-Air Temperature Sensor Drift Fault (Cooling Season Day 21)

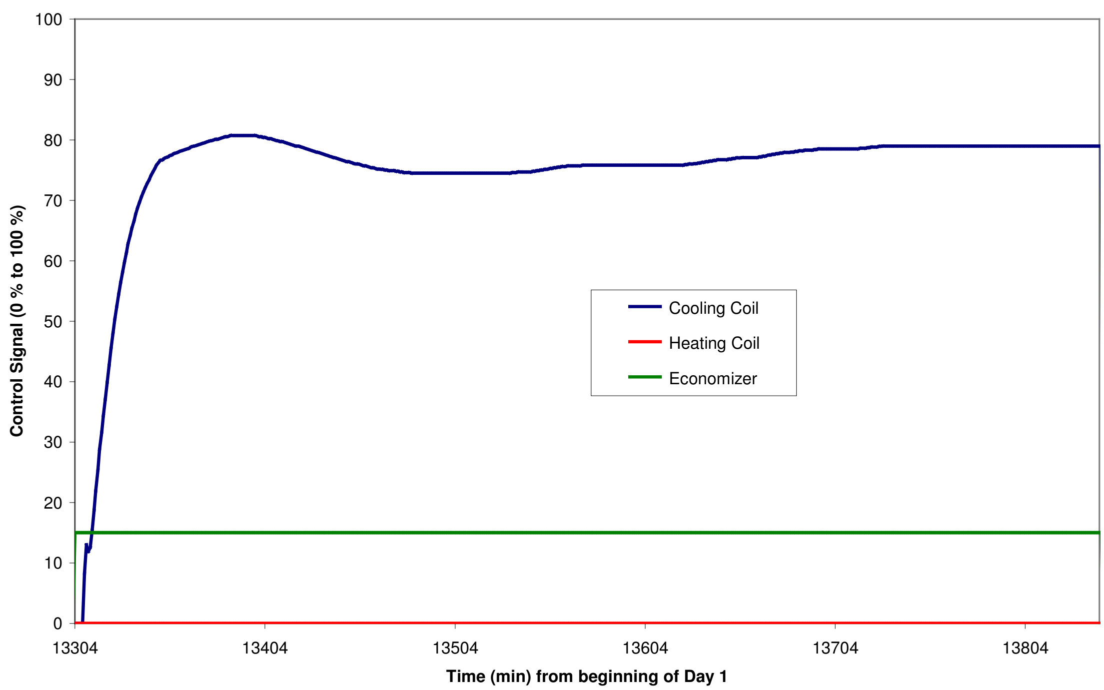


Figure 10 – VCBT AHU-3 Control Signal for Return-Air Temperature Sensor Drift Fault (Cooling Season Day 21)

5.6.4 Supply-Air Temperature Sensor Failure

This fault was introduced by sending a 10 VDC (volts direct current) signal to the terminal leads on the AHU-1 controller on which the supply-air temperature sensor was connected. This is a 0 to 10 VDC analog input calibrated to a range of 0 °F to 150 °F, so the 10 VDC signal is scaled to a supply-air temperature of 150 °F.

When this fault is introduced, the controller reads a supply-air temperature (light blue, Figure 11) of 150 °F, which is well above the supply-air temperature set point (dark blue, Figure 11) of 55 °F. The temperature control PID (proportional integral differential) loop in the AHU controller responds by opening the cooling coil valve (blue, Figure 12) until it saturates.

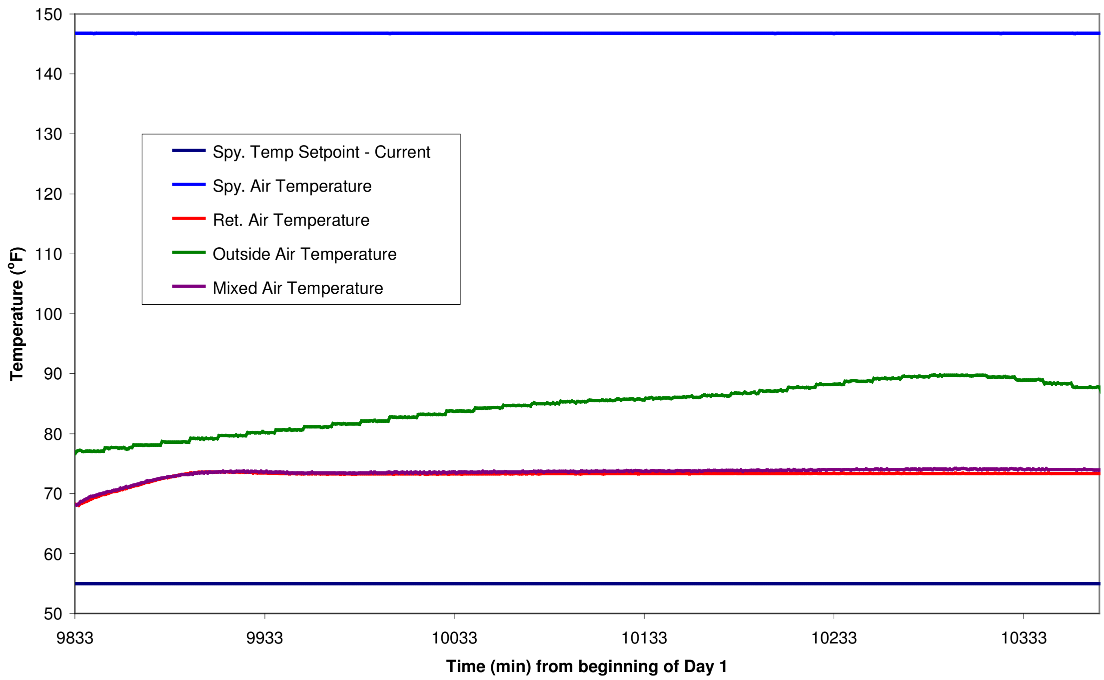


Figure 11 – VCBT AHU-1 Temperatures for Supply-Air Temperature Sensor Failure Fault (Cooling Season Day 15)

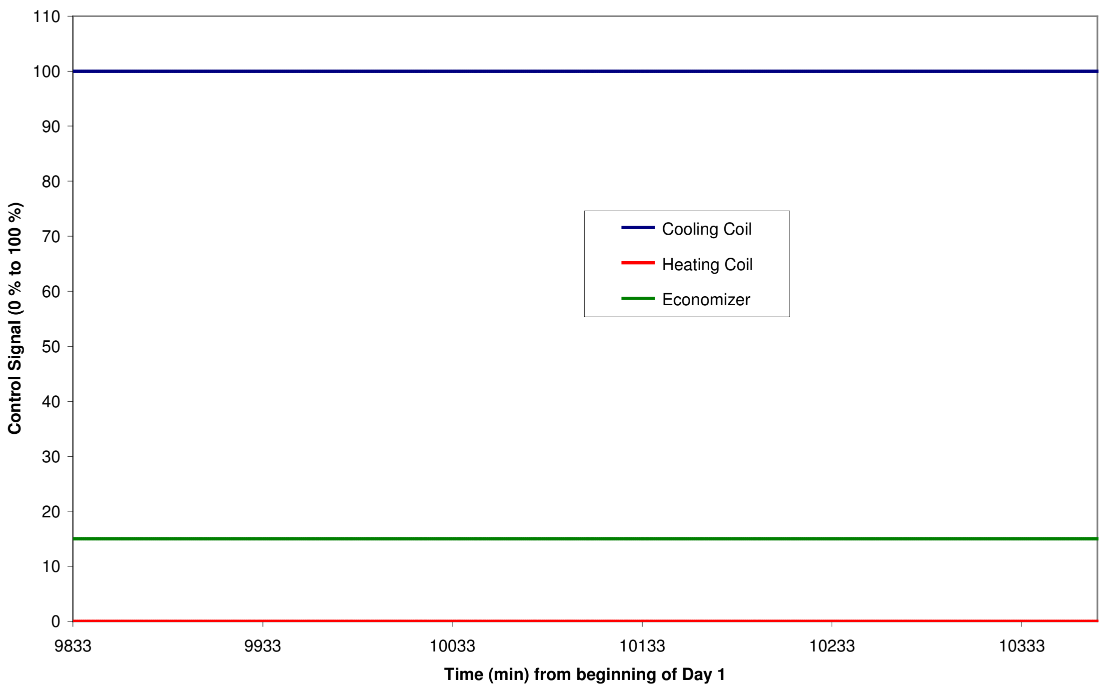


Figure 12 – VCBT AHU-1 Control Signals for Supply-Air Temperature Sensor Fault (Cooling Season Day 15)

5.6.5 Mixed-Air Temperature Sensor Failure

This fault was introduced by subtracting a large offset from the actual mixed-air temperature and sending the 0 to 10 VDC signal to the terminals on the AHU-3 controller on which the mixed-air temperature sensor was connected. In this case, the fault is introduced during heating season, when the economizer dampers blend the outdoor air and return air to maintain the mixed-air temperature at its set point. When this fault is introduced, the controller reads a very low mixed-air temperature (green, Figure 13), causing the mixed-air temperature control PID loop to respond by closing the economizer dampers (green, Figure 14) to the minimum position. The heating coil valve (red, Figure 14) and cooling coil valve (blue, Figure 14) temperature control PID loops both use supply-air temperature (light blue, Figure 13) as the controlled value, so both valves stay closed.

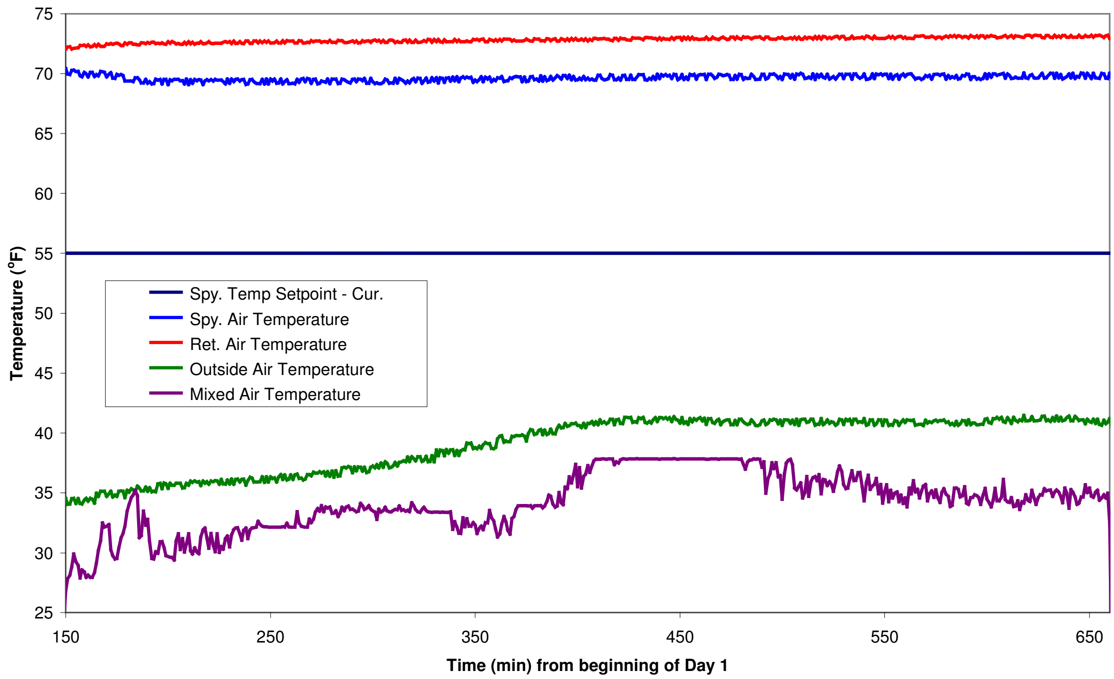


Figure 13 – VCBT AHU-1 Temperatures for Mixed-Air Temperature Sensor Failure (Cooling Season Day 21)

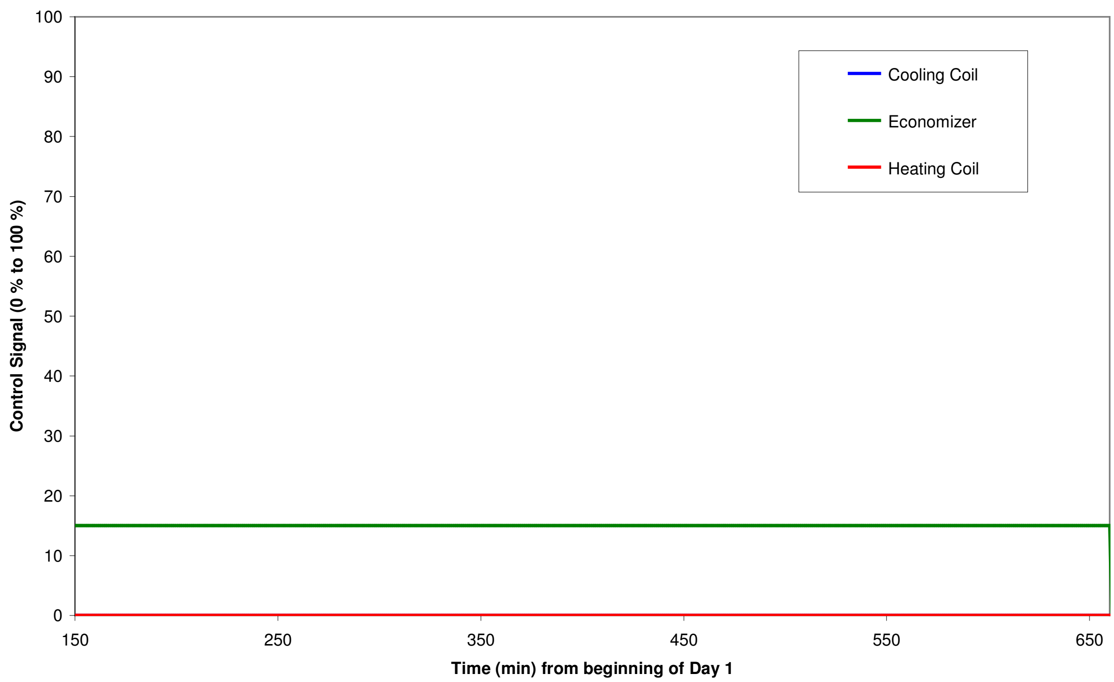


Figure 14 – VCBT AHU-3 Control Signals for Mixed-Air Temperature Sensor Fault (Heating Season Day 1). Both the heating and cooling controls signals are zero for the entire time period.

5.6.6 Outdoor-Air Temperature Sensor Failure

This fault was introduced by disconnecting the leads to the terminals on the AHU-1 controller on which the outdoor-air temperature sensor was connected. This is a 0 to 10 VDC analog input calibrated to a range of 20 °F to 120 °F, so with the leads disconnected, the controller reads 0 VDC, which is scaled to an outdoor-air temperature of 20 °F.

When this fault is introduced, the controller reads an outdoor-air temperature of 20 °F. The logic in the controller calculates outdoor-air enthalpy based on outdoor-air temperature and outdoor-air humidity, so the erroneously low reading of outdoor-air temperature will result in an erroneously low calculated value of outdoor-air enthalpy. The AHU-1 controller compares the calculated value of outdoor-air enthalpy to return-air enthalpy (calculated in a similar fashion based on return-air temperature and return-air humidity) and enables economizer operation if the outdoor-air enthalpy is less than the return-air enthalpy. The erroneously low calculated value of outdoor-air enthalpy will cause the controller to enable economizer operation, even if such operation is inappropriate.

Because the actual outdoor-air temperature is greater than the supply-air temperature set point, the mixing box dampers (green, Figure 15) will saturate at the 100 % outdoor air position, and the AHU controller will modulate the cooling coil valve (blue, Figure 16) to maintain the supply-air temperature at its set point. The heating coil valve (red, Figure 16) is closed.

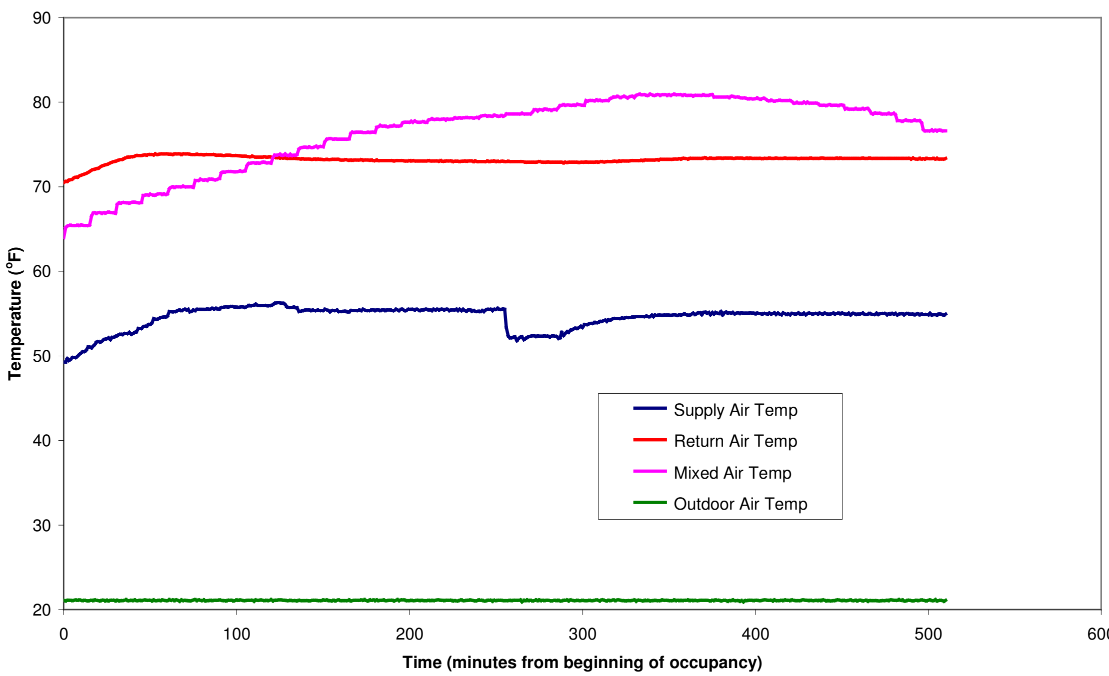


Figure 15 – VCBT AHU-3 Temperatures for Outdoor-Air Temperature Sensor Fault (Swing Season Data)

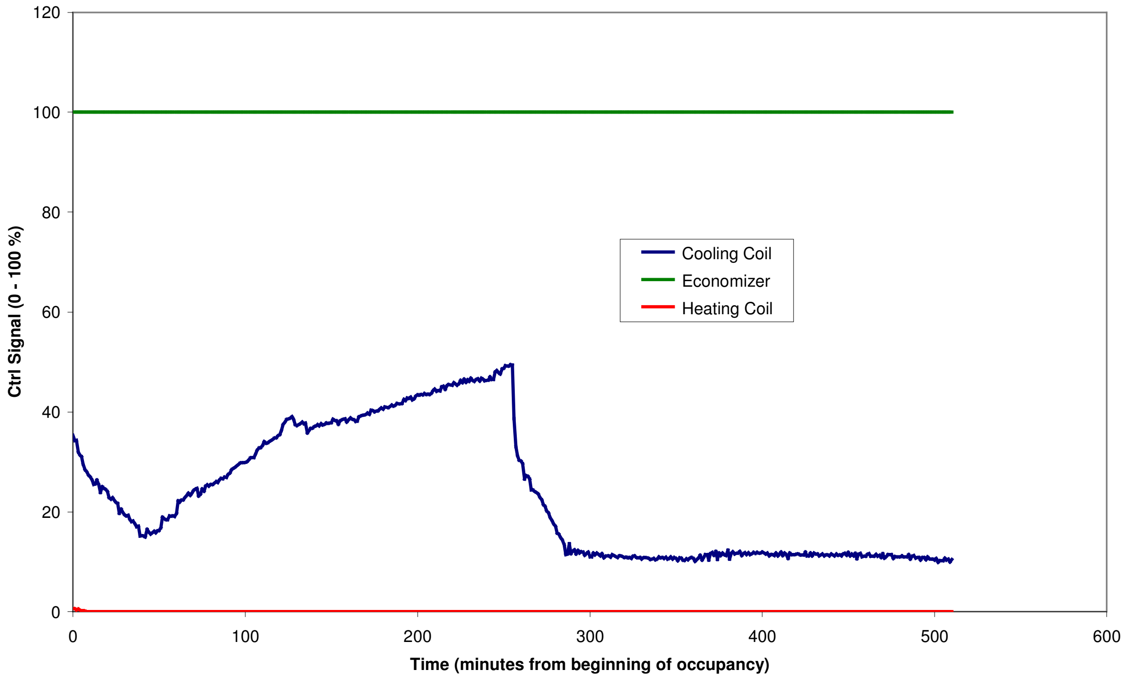


Figure 16 – VCBT AHU-3 Control Signals for Outdoor-Air Temperature Sensor Fault (Swing Season Data)

5.6.7 Recirculation Damper Leakage

When this fault is introduced, the AHU controller calculates the desired position of the damper and sets the damper control signal normally. If the damper control signal is less than 40 %, the damper position is set to the 40 % open position within the emulation. During emulation of this fault, the outdoor-air and exhaust-air dampers follow normal operation.

On this particular day, the outdoor-air temperature (green, Figure 17) and humidity (not shown) are low enough to permit economizing, and the mixing box dampers (green, Figure 18) saturate at 100 % open and the cooling coil valve (blue, Figure 18) is modulated to maintain the supply-air temperature (light blue, Figure 17) at its set point (dark blue, Figure 18). Under these conditions, the recirculation damper would normally be set to 0 % open (fully closed), but because of the leakage fault, some recirculation flow occurs. The qualitative effect of the leaking recirculation damper can be seen by comparing the mixed-air temperature (brown, Figure 17) to the return (red, Figure 17) and outdoor-air temperatures. If the dampers were aligned correctly, the mixed-air temperature should be very close to the outdoor-air temperature, but it is actually somewhere between the return-air temperature and the outdoor-air temperature, because of the return-air leaking through the recirculation damper.

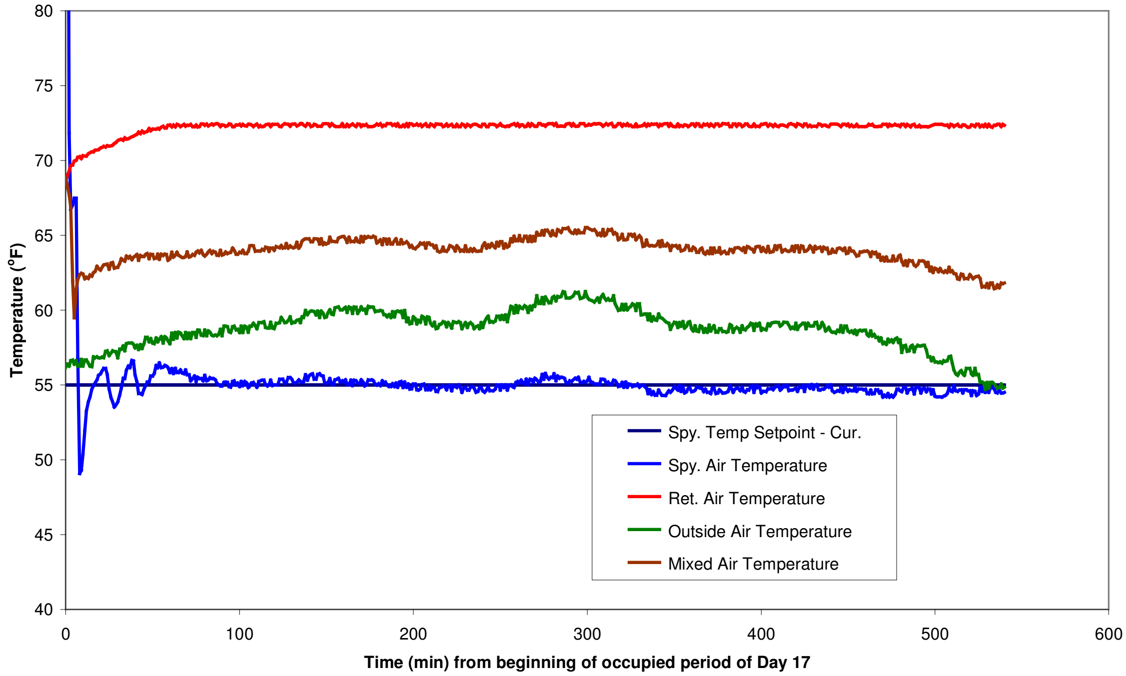


Figure 17 – VCBT AHU-3 Temperatures for Recirculation-Air (return-air) Damper Leakage Fault (Swing Season Day 17)

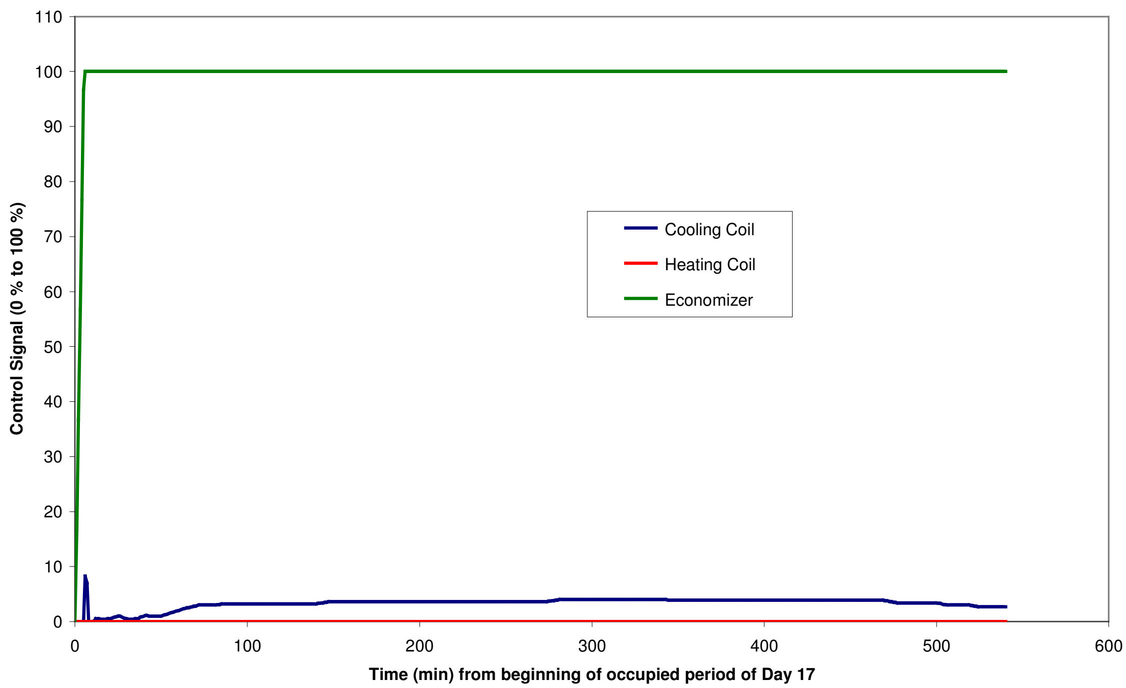


Figure 18 – VCBT AHU-3 Control Signals for Recirculation-Air (return-air) Damper Leakage Fault (Swing Season Day 17)

5.6.8 Stuck Outdoor-Air Damper

When this fault is introduced, the emulation overrides the outdoor-air damper control signal from the AHU and sets the position of the outdoor-air damper to the minimum position for ventilation (15 % open). During emulation of this fault, the outdoor-air and exhaust-air dampers follow normal operation.

On this particular day, the outdoor-air temperature (green, Figure 19) and humidity (not shown) are low enough to permit economizing, and the mixing box dampers (green, Figure 20) saturate at 100 % open and the cooling coil valve (blue, Figure 20) is modulated to maintain the supply-air temperature (light blue, Figure 19) at its set point (dark blue, Figure 19). Because of the fault, the actual percentage of outdoor air is much less than the 100 % indicated by the damper control signal. This can be seen qualitatively by comparing the mixed-air temperature (purple, Figure 19) to the return (red, Figure 20) and outdoor-air temperatures. If the outdoor-air damper were set as intended, the mixed-air temperature would be the same as the outdoor-air temperature, but it is actually somewhere between the outdoor-air temperature and the return-air temperature.

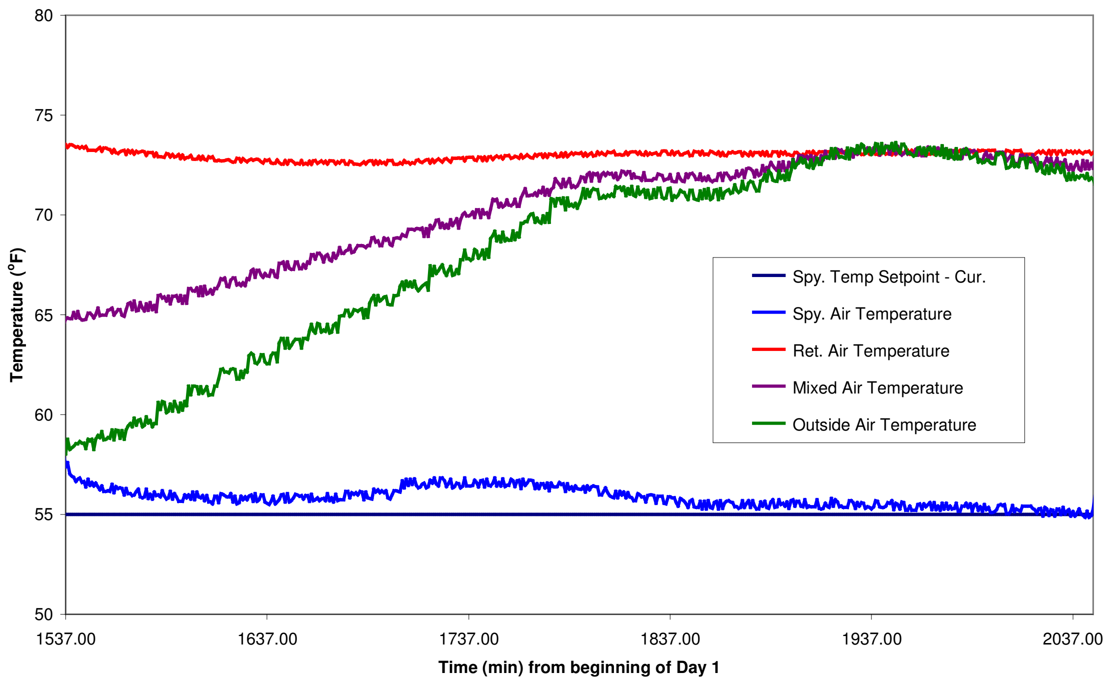


Figure 19 – VCBT AHU-3 Temperatures for Stuck Outdoor-Air Damper Fault (Swing Season Day 3)

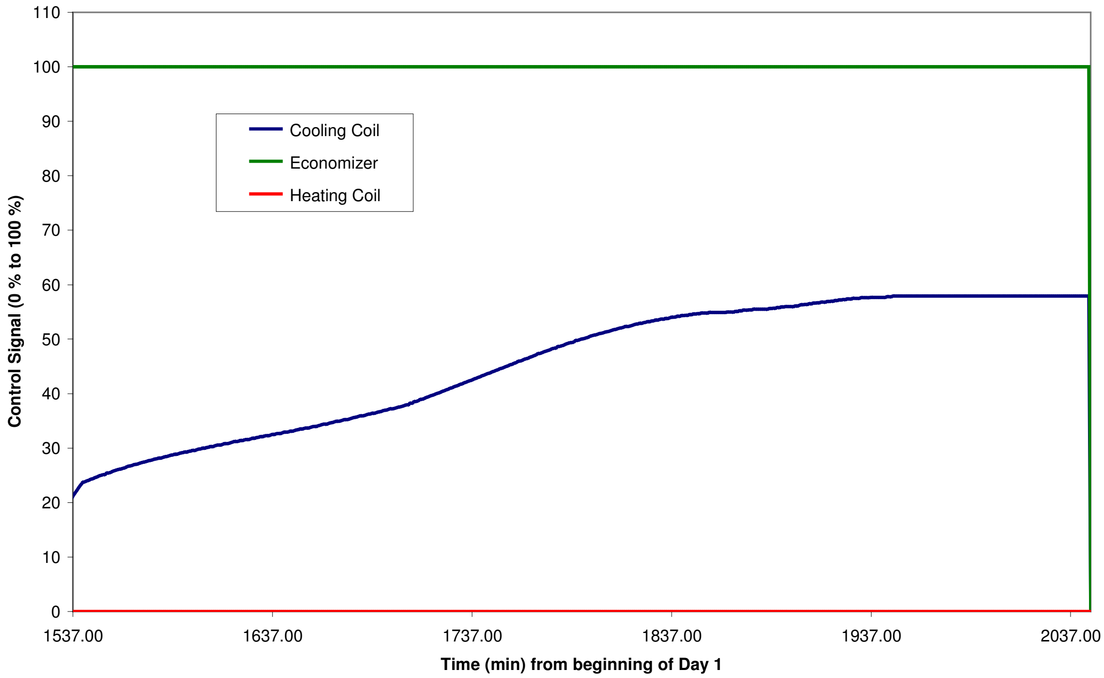


Figure 20 – VCBT AHU-3 Control Signals for Stuck Outdoor-Air Damper Fault (Swing Season Day 3)

5.6.9 Economizer Control Logic Fault

When this fault is introduced, the logic used to select economizer or minimum ventilation operation is reversed. The AHU-2 controller compares the outdoor-air temperature to a fixed changeover temperature, 72 °F, to determine whether to enable or disable economizer operation. Normally, economizer operation is disabled if the outdoor-air temperature is greater than the changeover temperature and enabled if the outdoor-air temperature is less than the changeover temperature, subject to a specified deadband, 2.0 °F. When the economizer fault is implemented, this relationship is reversed: economizer operation is enabled if the outdoor-air temperature is greater than the changeover temperature and disabled if the outdoor-air temperature is less than the changeover temperature, still subject to the specified deadband.

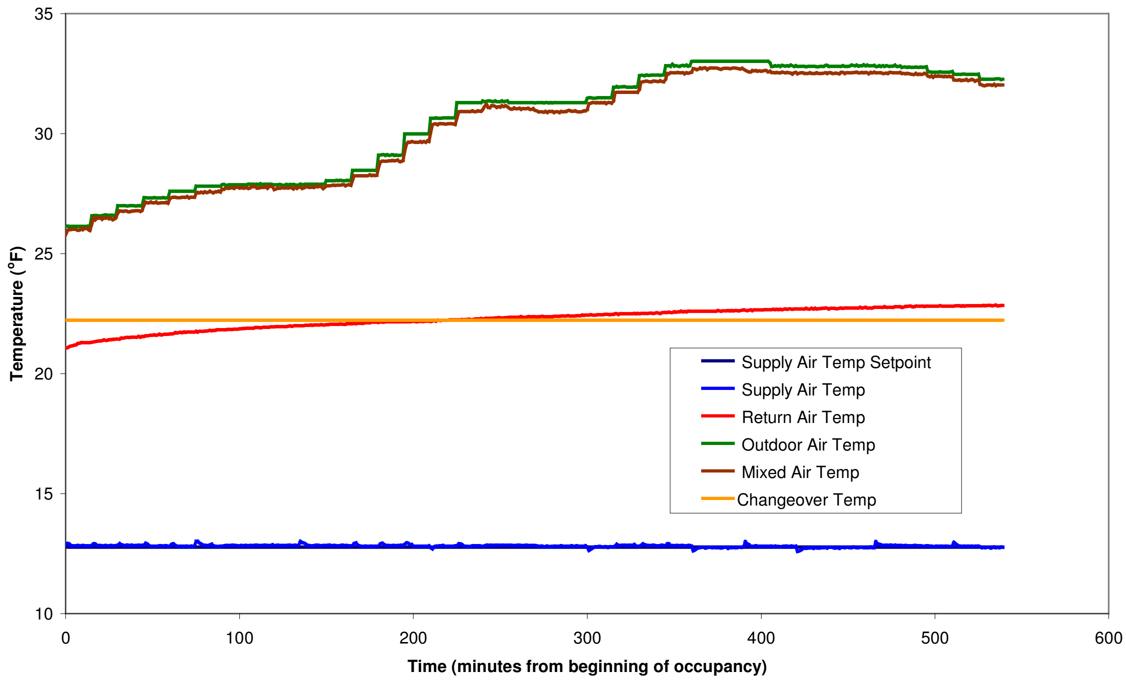


Figure 21 – VCBT AHU-2 Temperatures for Economizer Control Logic Fault (Cooling Season Data)

Figure 20 and Figure 21 show data from AHU-2 from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 20) ranges from 79 °F to 91 °F, which is greater than the changeover temperature (orange, Figure 20) by more than the deadband as is typically the case for cooling season. If AHU-2 was operating without any faults, these conditions would cause the AHU controller to disable the economizer and align the mixing box dampers to bring in the minimum amount of outdoor air needed for ventilation. Because of the control logic fault, the mixing box dampers (green, Figure 21) are actually aligned to bring in 100% outdoor air. Qualitatively, this can be seen by comparing the mixed-air temperature (brown, Figure 21) to the return (red, Figure 21) and outdoor-air temperatures (green, Figure 21). If the dampers were aligned for minimum outdoor-air, the mixed-air temperature would be very close to the return-air temperature, but actually the mixed-air temperature is nearly identical to the outdoor-air temperature, because the fault in the AHU control logic has positioned the dampers to bring in 100% outdoor air.

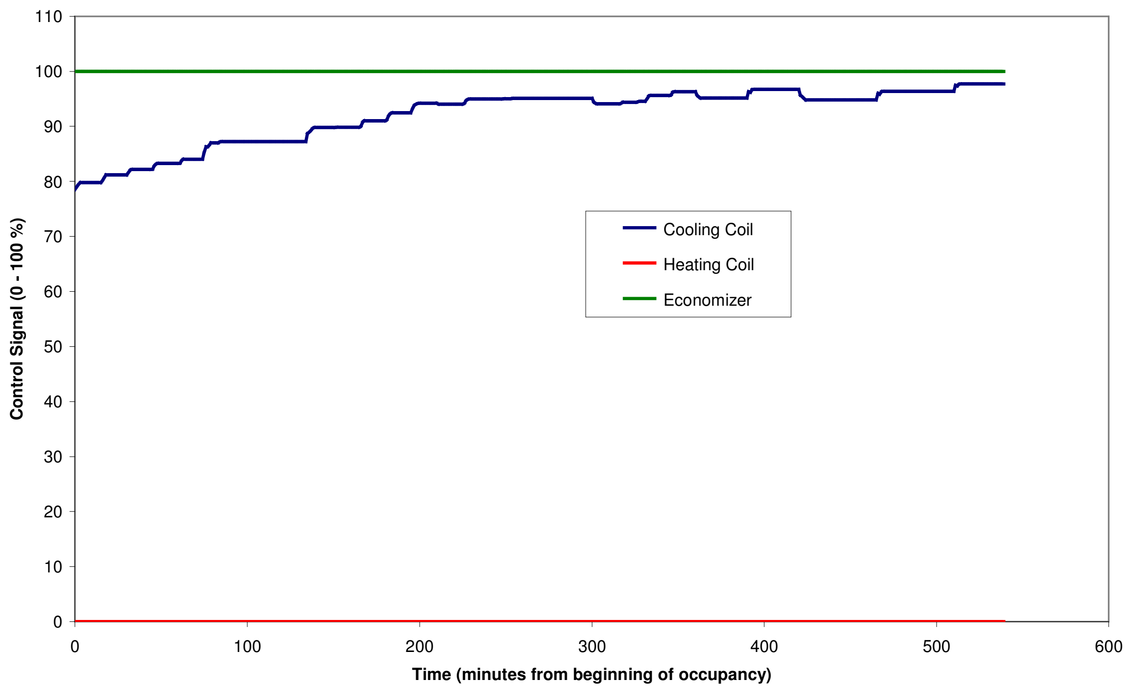


Figure 22 – VCBT AHU-2 Control Signals for Economizer Control Logic Fault (Cooling Season Data)

5.7 Data Generation for the WBE Module

The WBE module requires 9 months of training data, as well as several months of data for each fault; the use of the VCBT (which runs in real time) as a testing environment was not possible. Instead, a pure computer-simulation based on HVACSIM$^+$ was used, similar to the HVAC system and building shell simulation components of the VCBT.

The model simulates one floor of an office building and its associated mechanical equipment. A single duct AHU supplies air to three zones. Each zone is served by a variable-air-volume (VAV) terminal box. The AHU dampers, valves, coils, actuators, ducts, and fans, and the VAV box dampers, coils, and valves are represented by HVACSIM$^+$ component models. In addition, all sensors are represented by HVACSIM$^+$ component models. Most of component models used were originally developed for an ASHRAE research project and documented by Haves and Norford (1997).

For this study, the model was expanded to three floors, each of which is provided with an AHU and three VAV boxes as described above. In addition, chiller and boiler component models were added to compute electricity and gas energy consumption data for the WBE module.

5.8 Control Strategies

5.8.1 VAV Box

A pressure dependent VAV box control strategy is used. Two zone temperature set points, a heating set point (HSP) and a cooling set point (CSP), are defined (CSP > HSP). When the zone temperature is between the two set points, the VAV box damper is set at its minimum position for ventilation and the VAV box reheat coil valve is closed. If the zone temperature rises above the CSP, the damper is opened proportionally. If the zone temperature falls below the CSP, the reheat coil valve is opened proportionally.

5.8.2 AHU Fan Control

The supply-air fan speed is controlled to maintain the supply-air pressure at a fixed supply-air pressure set point. The return-air fan speed is controlled to maintain a constant difference between the supply-air and return-air flow rates.

5.8.3 AHU Temperature Control

A single PI control loop is used to determine a temperature control signal to maintain the supply-air temperature at a fixed supply-air temperature set point. Depending on the magnitude of the signal, it is mapped to one of three outputs which control the heating coil, cooling coil, or mixing-box dampers. For example, if the heating coil valve is active, the cooling coil valve will be fully closed and the mixing box damper will be set to the minimum position (which depends on the occupancy status). The outdoor-air and the return-air enthalpies are compared to determine whether to enable or disable economizer operation.

5.8.4 Boiler

The boiler control strategy is similar to that described by Kohonen et al. (1993). The boiler is turned on the whole year, because the reheat coils need the hot water to maintain the zone temperatures at or near the zone-air temperature set points. A fossil-fuel-fired hot water boiler is used. The boiler employs an on-off control scheme. The boiler on-times and off-times are determined based upon demand.

5.8.5 Chiller

The chiller control strategy is similar to that described by Wang (1992). The chiller is turned on from April 21 until October 31. The chiller operation implements a proportional control scheme, in which the evaporator outlet water temperature is maintained at its set point by varying the capacity of the chiller.

5.9 WBE Normal Operation

Data from a one year fault free emulation are presented to highlight normal operation. Figure 23 and Figure 24 show electricity and gas consumption data respectively. The lighting and equipment electrical load (dark blue, Figure 23) and the HVAC electrical load (yellow, Figure 23) vary between occupied and occupied values, however, the daily load profiles are constant throughout the year. The chiller (purple, Figure 23) consumes electrical energy during the late spring, summer, and early fall months, with the consumption trend following the outdoor conditions, with some lag. The boiler gas consumption (blue, Figure 24) is greatest during the winter months, falling off as the outdoor conditions moderate. There is still a residual level of gas consumption during nominally cooling conditions, for morning warm-up or when the cooling load is small and the cooling effect of the VAV boxes' minimum air flow rate causes the zone temperature to drop below the cooling set point.

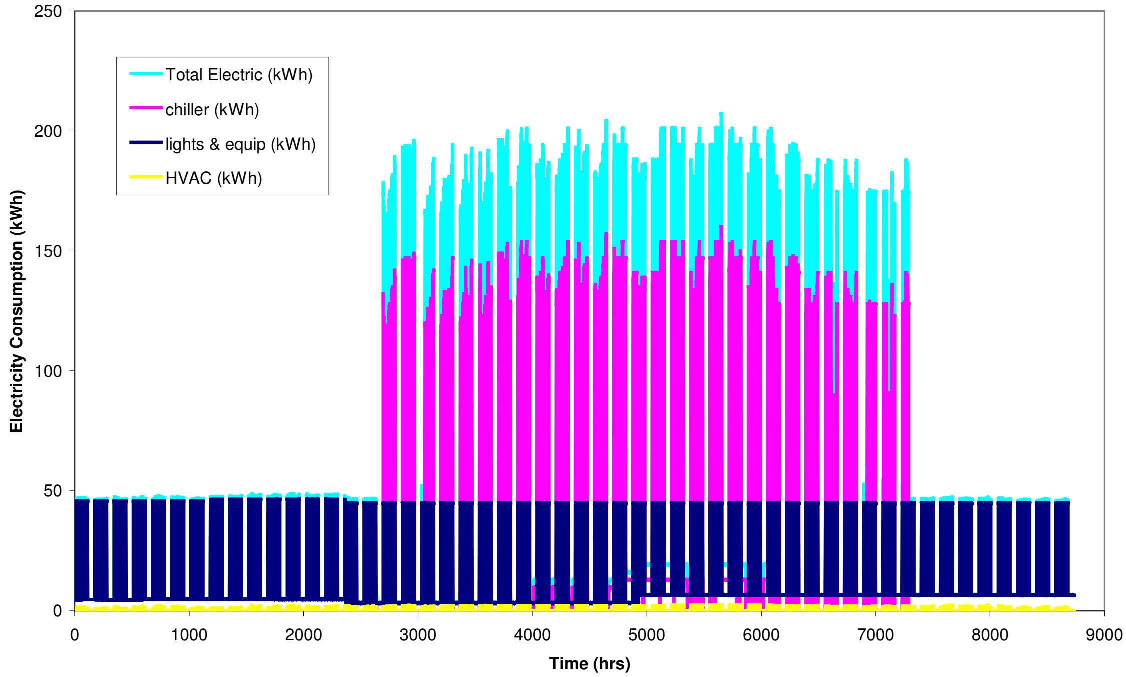


Figure 23 – Simulated End-Use Electricity Consumption for Normal Operation

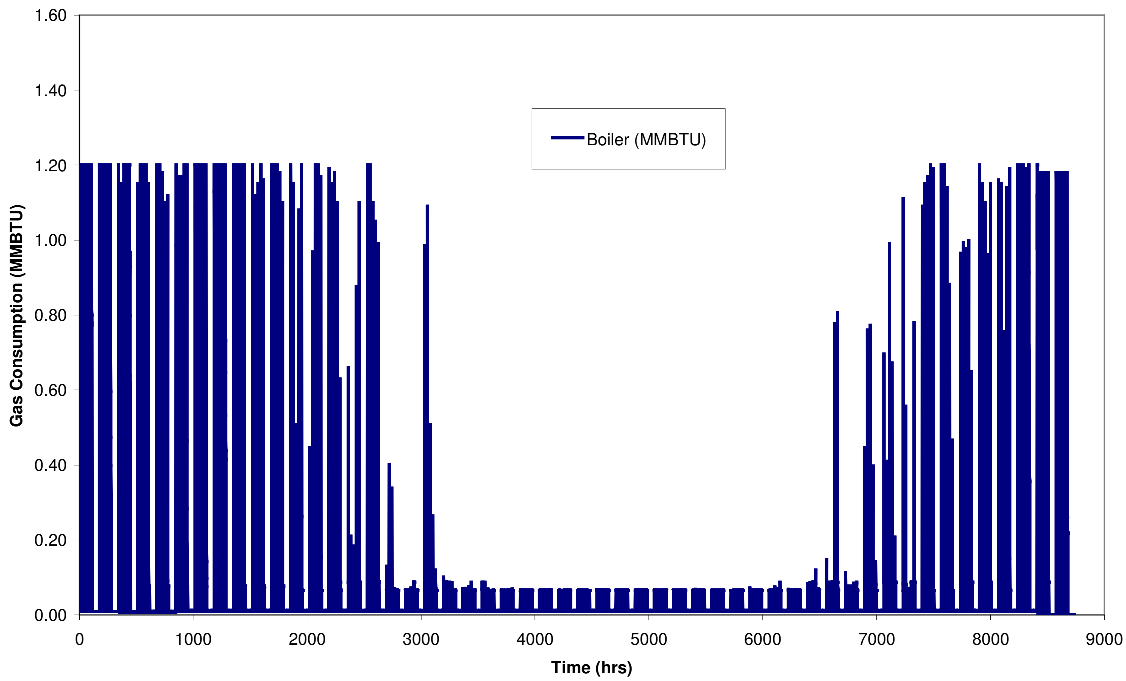


Figure 24 – Simulated End-Use Gas Consumption for Normal Operation

5.10 WBE Faulty Operation

The following faults were included in the blind tests of the WBE module.

5.11 Increase in HVAC Electrical Energy Consumption

This fault is implemented by increasing the HVAC electrical energy consumption by 10 % during the period the fault is instigated, as illustrated in Figure 25 (fault-free) and Figure 26 (10 % increase in HVAC electrical energy consumption).

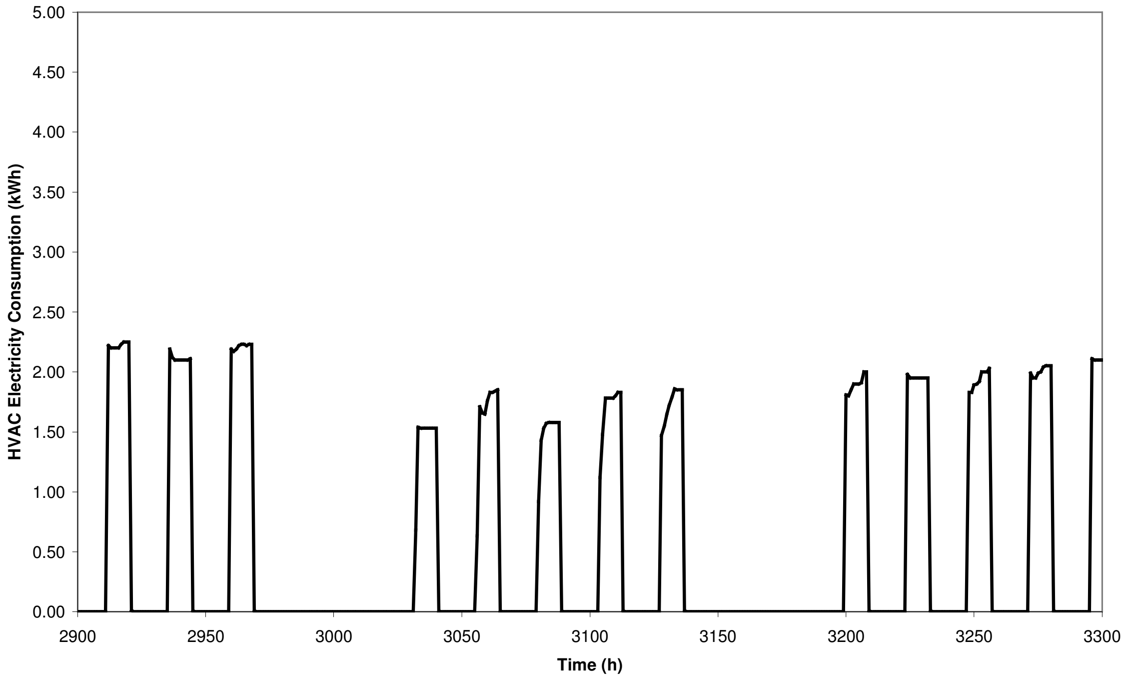


Figure 25 – Simulated HVAC Electricity Consumption for Normal Operation

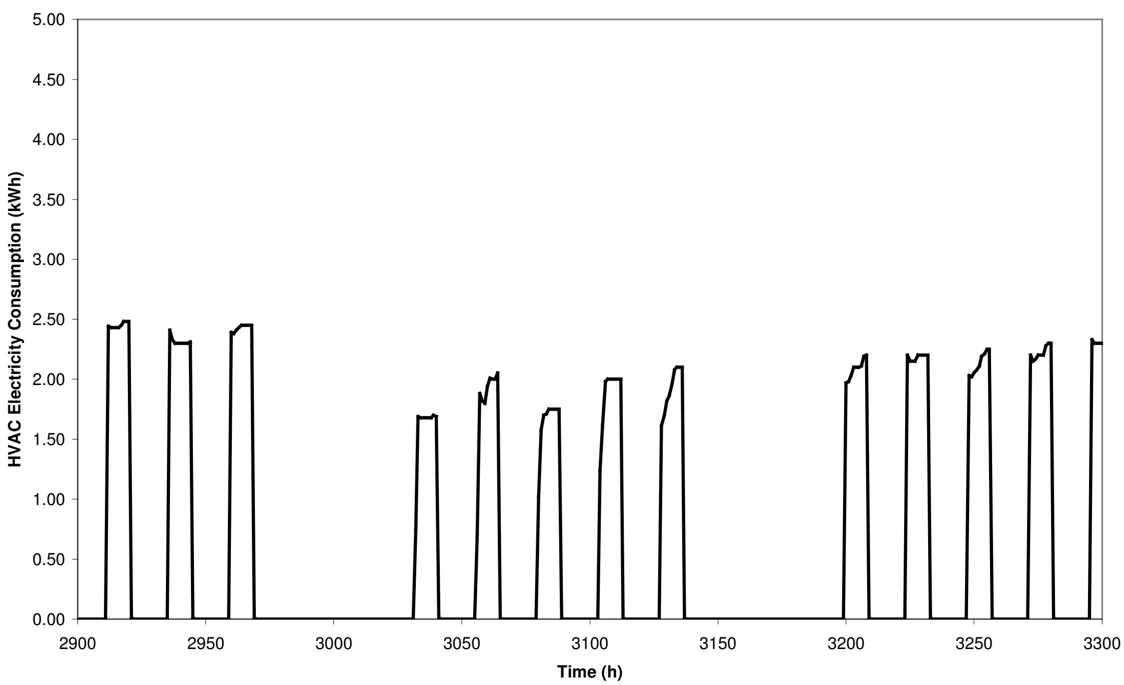


Figure 26 – Simulated HVAC Electricity Consumption with "Faulty" Operation

5.12 Increase in Boiler Gas Consumption

This fault is implemented by increasing the boiler gas consumption by 15 % during the period the fault is instigated, as illustrated in Figure 27 (fault-free) and Figure 28 (15 % increase in boiler gas consumption).

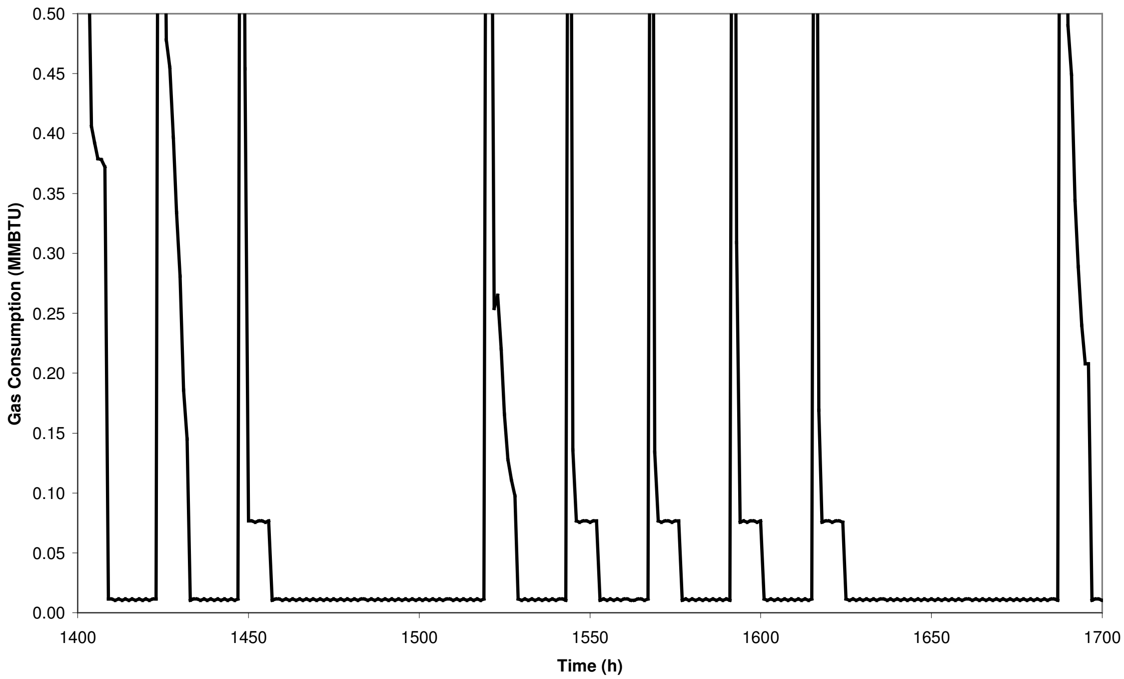


Figure 27 – Simulated Fault-Free Boiler Gas Consumption

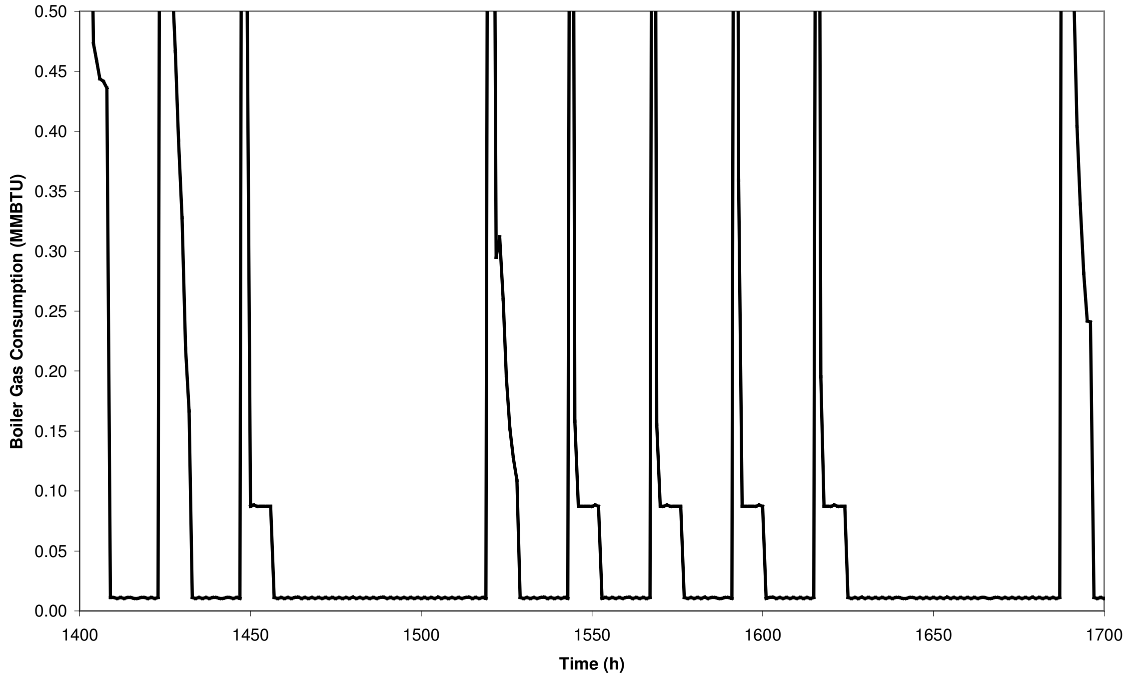


Figure 28 – Simulated Boiler Gas Consumption Representing "Faulty" Operations

5.13 Scheduling Problem

This fault is implemented by removing the scheduling related to reduced loads on weekends as opposed to weekdays, as illustrated in Figure 29 (fault-free) and Figure 30 (15 % scheduling problem).

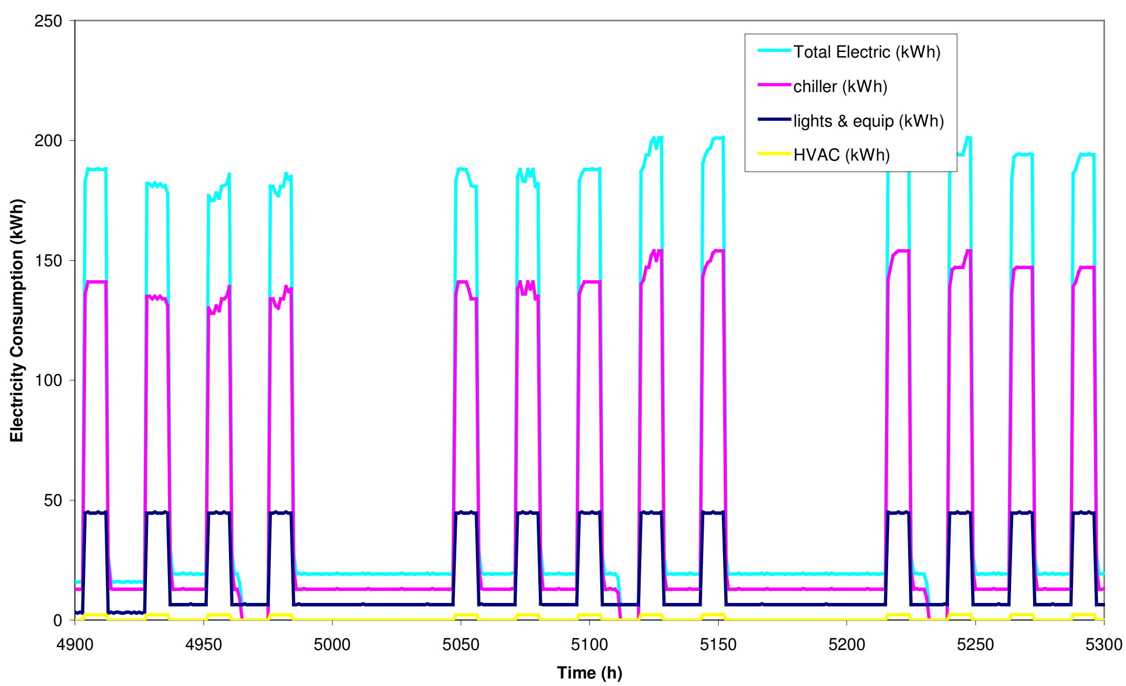


Figure 29 – Simulated Fault-Free Electricity Consumption

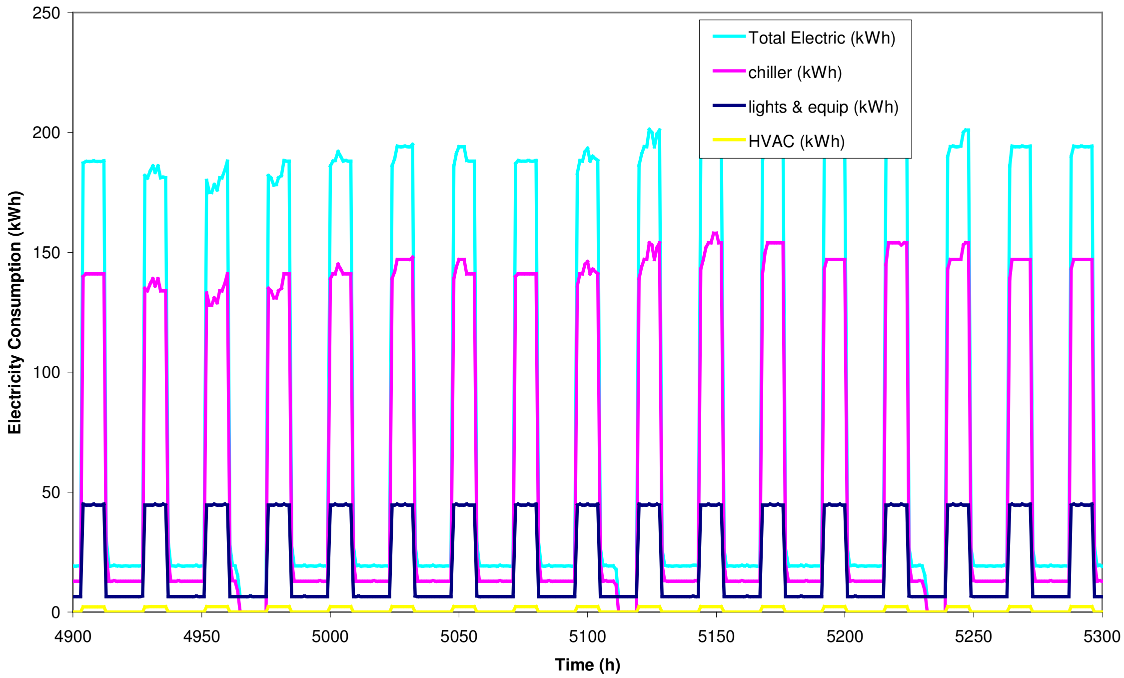


Figure 30 – Simulated Scheduling Problem for Electricity Consumption

5.14 Progressively Developing Increase in Chiller Electrical Energy Consumption

This fault is implemented by increasing the chiller electrical energy consumption linearly from 0 % to 25 % during the period the fault is instigated, as illustrated in Figure 31 (0 % to 25 % increase in chiller electrical energy consumption).

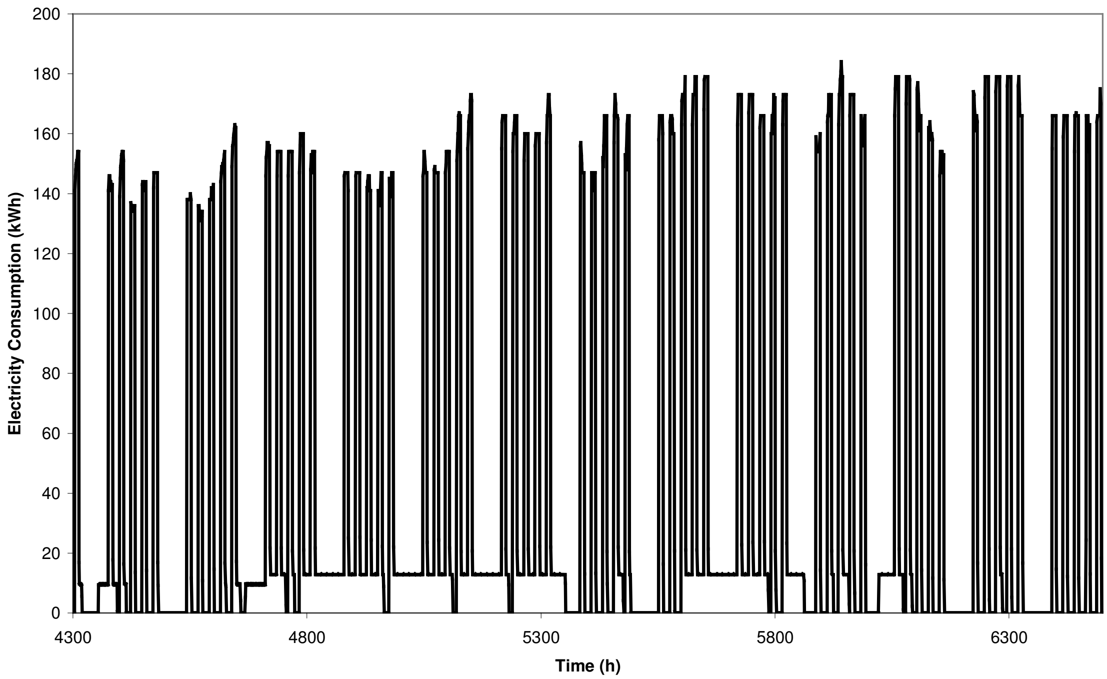


Figure 31 – Simulated Progressively Developing Chiller Fault

6 OAE Results

The results from automated processing of data sets with fault-free operation, operation with known faults, and operation with unknown faults (blind test) are presented in this section. All data sets with the exception of those with known faults have at least 3 weeks of data. The three data sets with known faults only have 1 week of data.

The OAE uses a rule-based methodology, which relies on comparison tests between variables to traverse a decision tree. These comparison tests account for random noise and measurement uncertainty to ensure reasonable levels of confidence in the decisions.

In the OAE module, tolerances are predefined for each measured and static input variable to account for the uncertainty in measured values[2]. The tolerances are propagated through all calculations and tests. For example, to test if the outdoor-air temperature is greater than the return-air temperature, not only should the outdoor-air temperature value be greater than the return-air temperature, it should be greater than the return-air temperature plus the uncertainty of the difference between the two measured values to minimize the probability that the true outdoor-air temperature is less than or equal to the return-air temperature. Similarly, the uncertainty associated with other algebraic combinations of measured variables and tests are evaluated using standard formulas for the propagation of errors in calculations (see, for example, Croarken and Tobias 2002). The tolerances assigned to each variable account for the actual uncertainty in the measured values including measurement uncertainty (or accuracy) specified by the sensor manufacturer. For example, a typical commercial-grade temperature sensor is accurate to about $\pm 0.5^{o}$F to $\pm 1^{o}$F.

The OAE diagnostician has five levels of detection sensitivity selectable by users. Increasing the detection sensitivity increases the ability to detect faults and decreases the rate of undetected faults (false negatives) while it also increases the probability of false alarms (i.e., false positives). Properly selecting the sensitivity setting is critical to achieve the desired balance between these factors. This presents a tradeoff to the user, who must subjectively judge which sensitivity setting is best, based on experience with the tool. Because noise and bias are unique to each specific combination of sensor and data acquisition equipment installed on an HVAC system and the environment in which it operates, selection of proper setting may vary from building to building or even between HVAC units in the same building. In general, we recommend setting the sensitivity at the middle of the sensitivity range (i.e., the normal setting). Initially, when data are processed with normal sensitivity setting and the AHU operation is found to be fault free, the user might choose to increase the sensitivity to see whether any faults are detected. Similarly, if experience shows that the OAE detects faults with little energy or operational impact, the user might opt to decrease the sensitivity so the OAE only reports faults with significant impacts. Because of differences in equipment among buildings and differences in preferences among

[2] Actually, although the OAE method, in principle, provides for adjusting tolerances individually, in the OAE software, all tolerances are adjusted simultaneously by the user selecting a sensitivity level for the tool. This approach is used to simplify user interaction with the tool.

users, we recommend that each user empirically adjust the sensitivity level to obtain the desired OAE performance.

6.1 OAE Diagnostic Approach

The OAE uses color in its display to alert users to the presence of faults with a result provided for each hour. Each color designates a different category of fault (and the absence of faults). In addition to providing easily seen indicators of faults, it also provides more complete descriptions of detected faults and for each fault a list of possible causes and suggested actions to correct the faulty operation. Because of uncertainly in measurements and ever changing indoor and outdoor conditions, the fault may or may not manifest continuously or during consecutive hours. In some cases, the fault may appear for a few hours and then may not appear again for several weeks or months (see, for example, Figure 55 for Test Z3-SS-F5C). As a result, it is difficult to devise a systematic process to help guide users in every situation. We provide users with general guidance on use of the OAE, but have not yet developed a catalog of specific situations. The ability and experience of the user plays a significant role in how the diagnostic tool is used.

6.2 Naming Convention for the Data Sets

The naming convention used to name data sets has the form Z1-CS-F10. The first part represents the virtual zone in the VCBT environment, for example, Z1 is used to denote zone 1 of the VCBT environment. The second part of the data set name identifies the part of the weather data used in the simulation. For this part, “CS” represents cooling season, “HS” represents heating season, and “SS” represents swing season (i.e., spring or fall). The third part is a number for the blind test, which is assigned by NIST.

6.3 OAE Results from Normal Operation

In this section, the OAE results for fault-free AHU operation are described. Using the VCBT simulation/emulation environment, NIST generated nine fault-free data sets, which represented normal AHU operation, three each for cooling, heating and swing seasons. The VCBT environment has three zones with each zone having an AHU. Two AHUs use enthalpy based differential controls for economizer operation, while the third uses differential dry-bulb controls. All three AHUs operate between 8 a.m. to 5 p.m., 7 days a week. After configuring the OAE diagnostician with proper control strategies and schedules, the nine fault-free data sets were processed.

The OAE diagnostician found no systematic errors with any of the nine fault-free data sets; however, it reported a few random errors. The 9 data sets have 6 to 8 days of data; all data sets are labeled as starting on the same day (February 1, 2001), although they represent different seasons (for convenience).

Diagnostic results for AHU-1, which serves virtual zone 1 in the VCBT, are shown in Figure 32. Six days of heating-season weather data were used in simulation of normal operation for AHU-1. As seen in Figure 32, all cells during occupied times are “white,” indicating that the AHU operation is fault free. Diagnostic results for AHU-2, which serves virtual zone 2 in the VCBT, are shown in Figure 33. Seven days of cooling season data are used in the simulation of normal operation for AHU-2. In this case, there are several “gray” cells and a single “red” cell. When indoor and outdoor conditions are nearly equal or if certain data are missing, the OAE can not perform diagnosis for that hour and it assigns gray to the corresponding cell. In this case, none of the data were missing, but the mixed and indoor conditions were nearly equal, as shown in Figure 34. Although the weather data was from cooling season, there were several hours with temperatures around 75°F. Diagnostic results for AHU-3, which serves virtual zone 3 in the VCBT, are shown in Figure 35. Six days of swing-season weather data was used in simulation of normal operation for AHU-3. In this case, there are several "gray" cells and a single "red" cell. The red cells that appeared in Figure 33 and Figure 35 appear to be random.

As seen from the representative results (fault-free) shown in Figure 32, Figure 33, and Figure 35, the simulation of normal operation is fault-free, with a few exceptions. This confirms that 1) the VCBT environment has generated fault-free data as specified, 2) the user specified inputs including the sensor accuracies are set properly in the OAE module, and 3) the economizer controls and operating schedules for each of the three AHUs are correctly set.

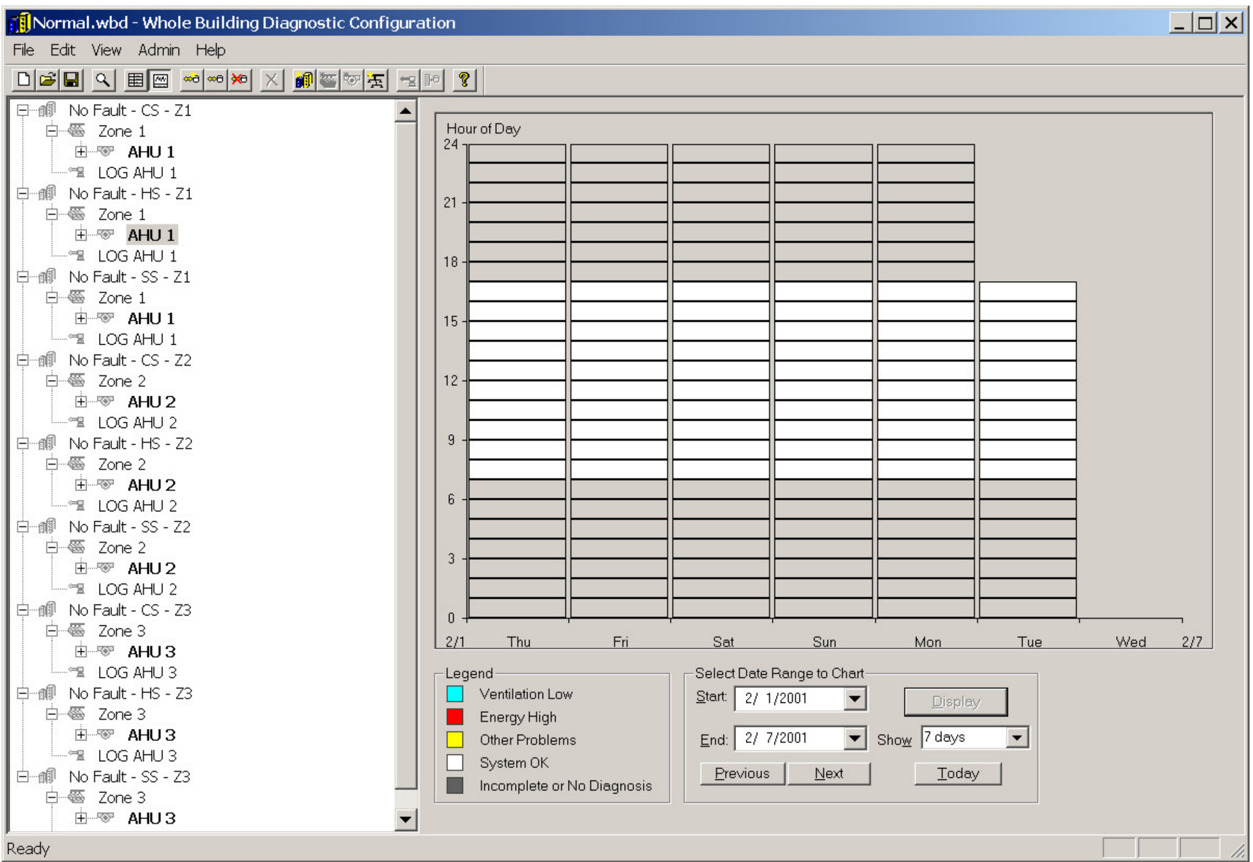


Figure 32 – OAE Diagnostic Results for AHU-1 with Fault-Free Data from the Heating Season (Z1-HS-FX)

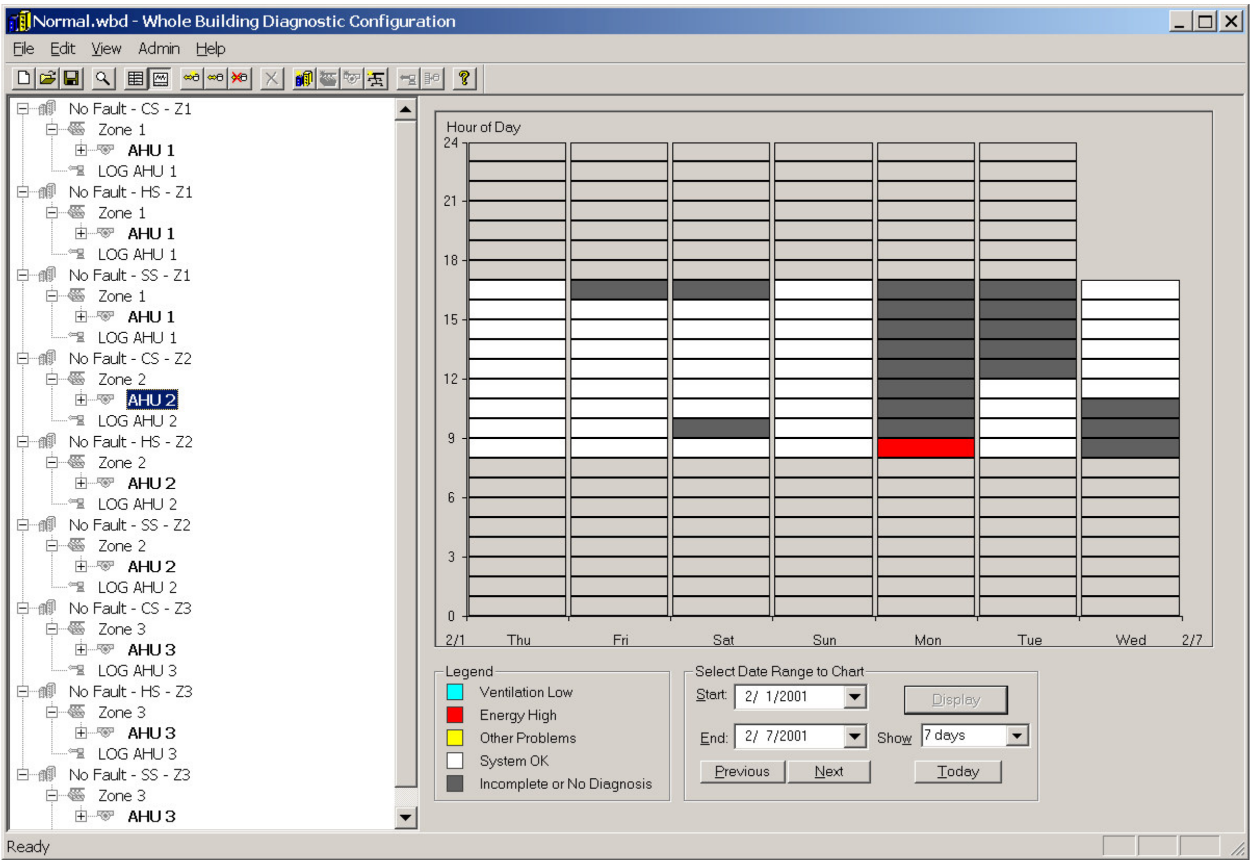


Figure 33 – OAE Diagnostic Results for AHU-2 with Fault-Free Data from the Cooling Season (Z2-CS-FX)

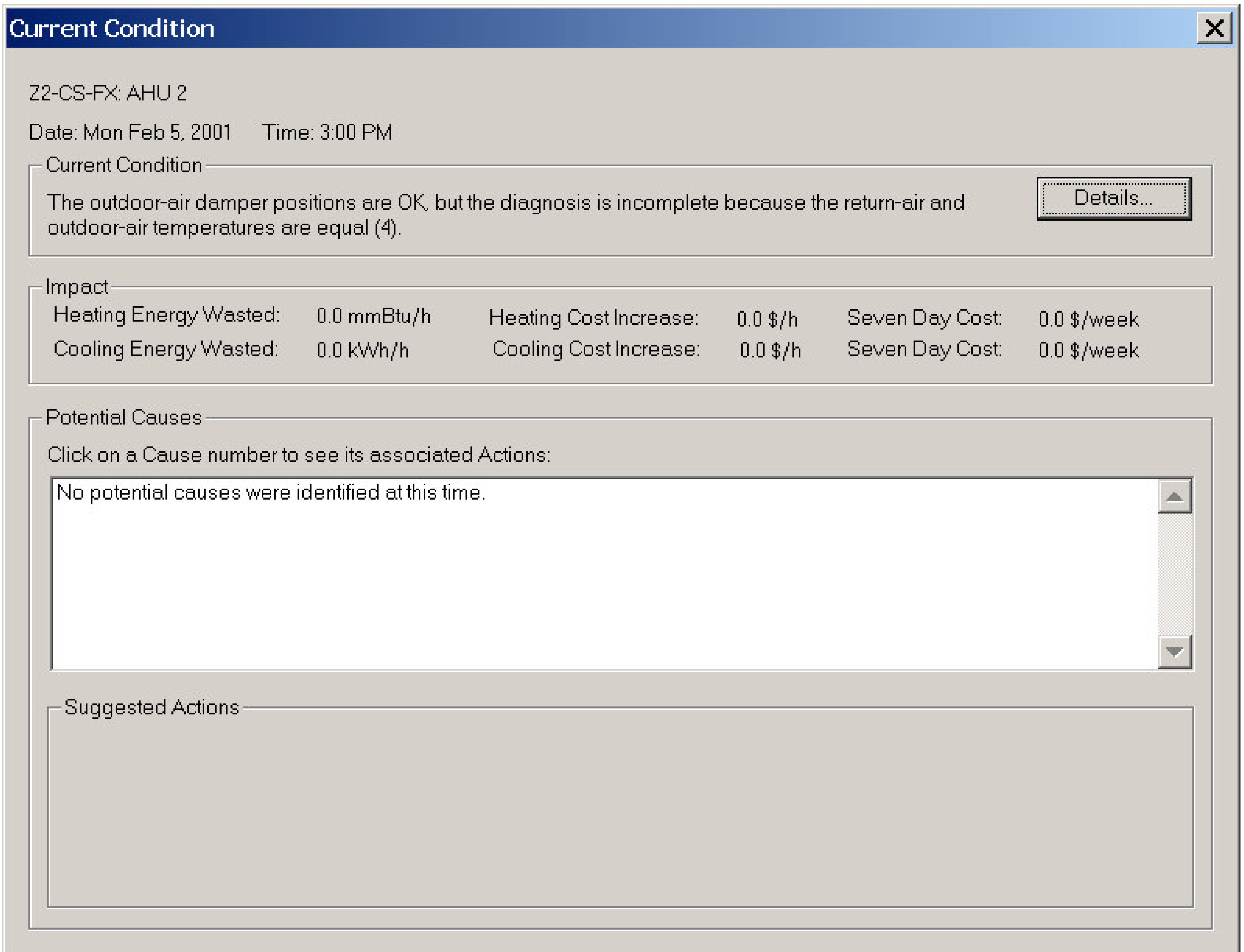


Figure 34 – Current Conditions Dialogue that shows Conditions for 3:00 p.m. on February 5, 2001 (Z2-CS-FX)

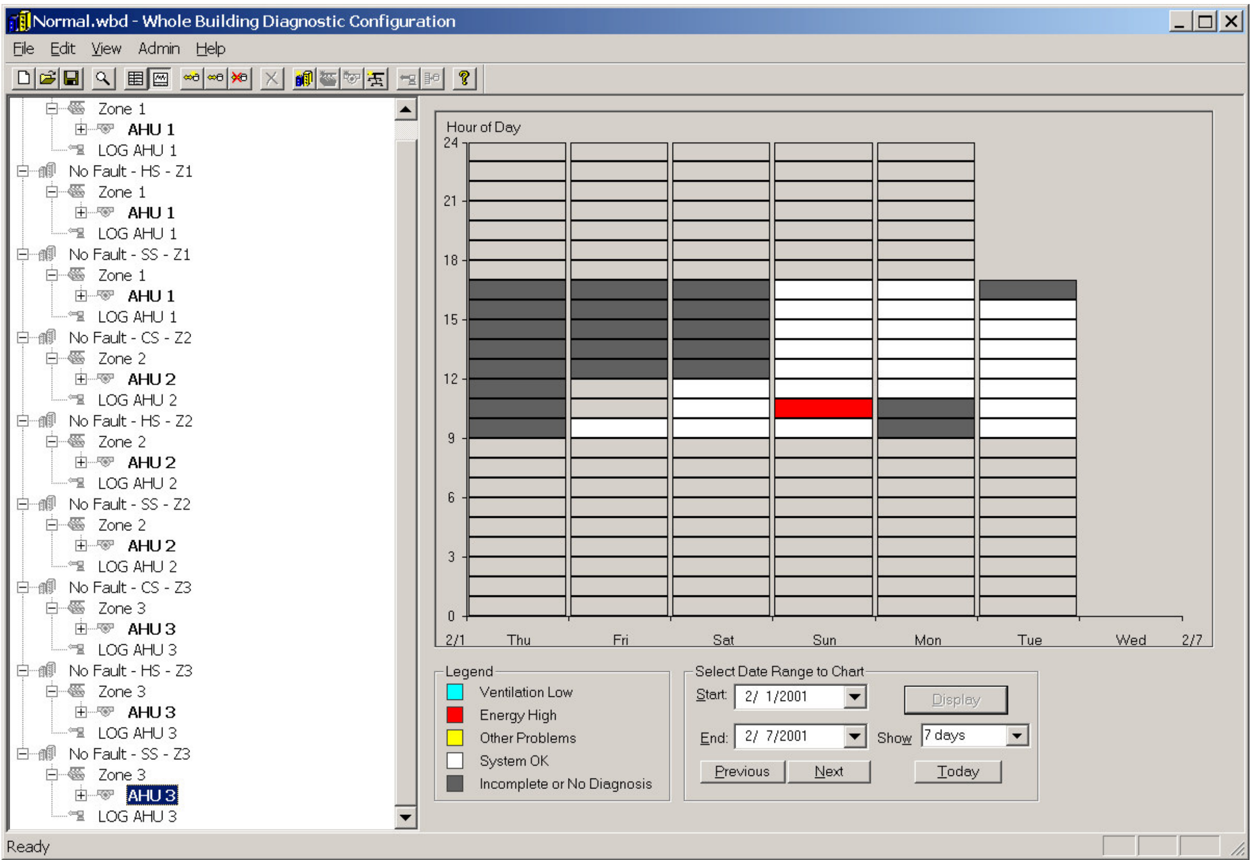


Figure 35 – OAE Diagnostic Results for AHU-3 with Fault-Free Data from the Swing Season (Z3-SS-FX)

6.4 OAE Results for Non-Blind Tests

After validating the configuration of the AHUs and the ability of the VCBT to generate fault-free data, the next step was to confirm the capability of the VCBT to generate "faulty data" that represents improper AHU operation. Using the VCBT environment, NIST generated three data sets with known faults for non-blind tests. Each of the "faulty data" sets was 1 week long and represented the cooling season. The three faults simulated were: 1) return-air damper stuck in a fully-closed position, 2) faulty economizer control logic, and 3) mixed-air temperature sensor drift. All data sets are labeled as starting on February 14, 2001 (for convenience), although the weather data used in the simulation represents the cooling season.

6.4.1 Return-Air Damper Stuck Fully Closed (Z1-CS-F10)

The data set named Z1-CS-F10 was created using cooling season weather data and represents an AHU operation with the return-air damper stuck in a fully closed position. The OAE diagnostic results for this data set are shown in Figure 36. The fault was instigated by overriding the control signal to return-air damper motor to make it remain in the closed position irrespective of the controller's damper command signal. When the return-air damper is stuck fully closed, only outdoor air is used. In general, this is not a problem when outdoor conditions are favorable for economizing. When the conditions are not favorable for economizing, however, the outdoor-air damper will be aligned at the minimum position. Under these conditions, more than the minimum outdoor-air is drawn through the outdoor-air dampers because the return-air dampers are closed. This is faulty operation, and the OAE should recognize this as such. However, the diagnostic results shown in Figure 36 indicate otherwise, where all cells are white indicating no faults were found.

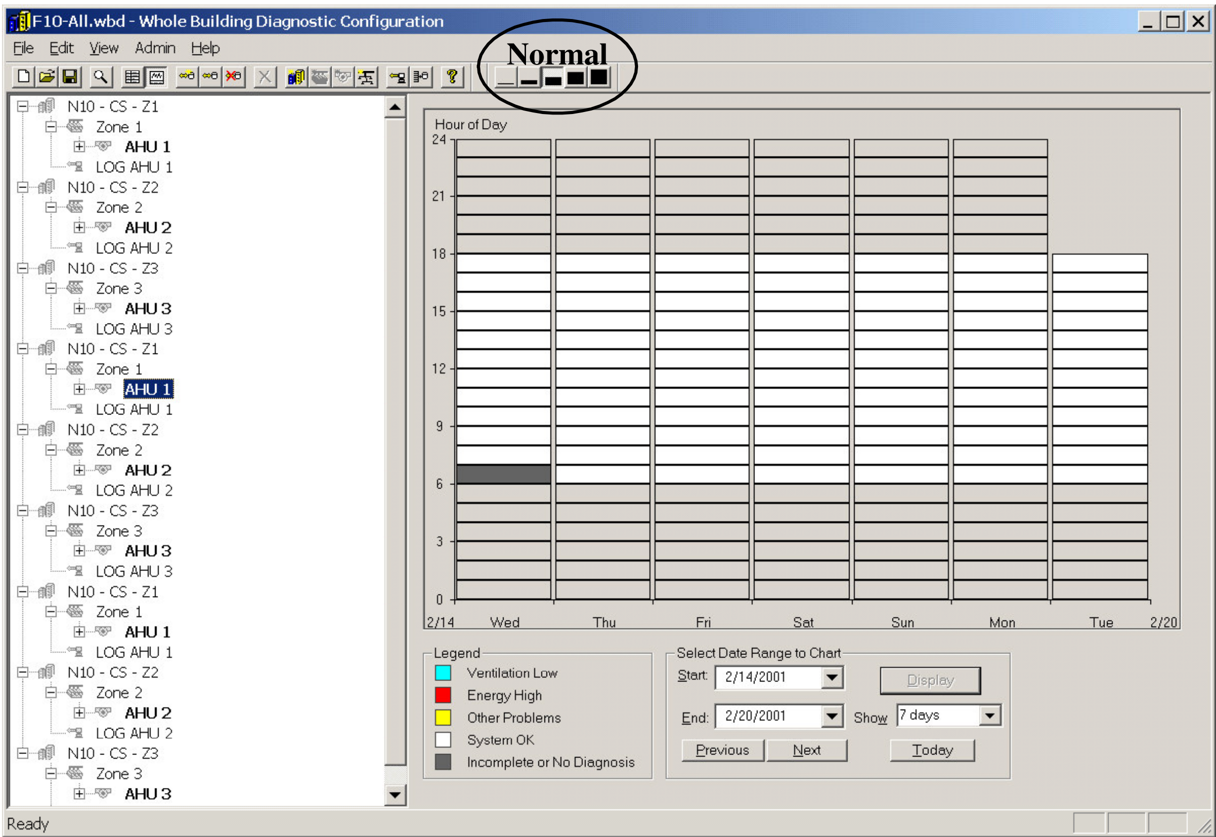


Figure 36 – OAE Diagnostic Results for AHU-1 with the Return-Air Damper Stuck in a Fully Closed Position for the Normal OAE Sensitivity Setting (data set Z1-CS-F10)

As noted in the previous section, the OAE has five levels of sensitivity. By default the OAE module is set at normal sensitivity (level 3), which is a mid-level sensitivity. The diagnostic results shown in Figure 36 were generated using normal sensitivity. To increase fault detection sensitivity, the sensitivity level was increased to High (level 5) and the data reprocessed (

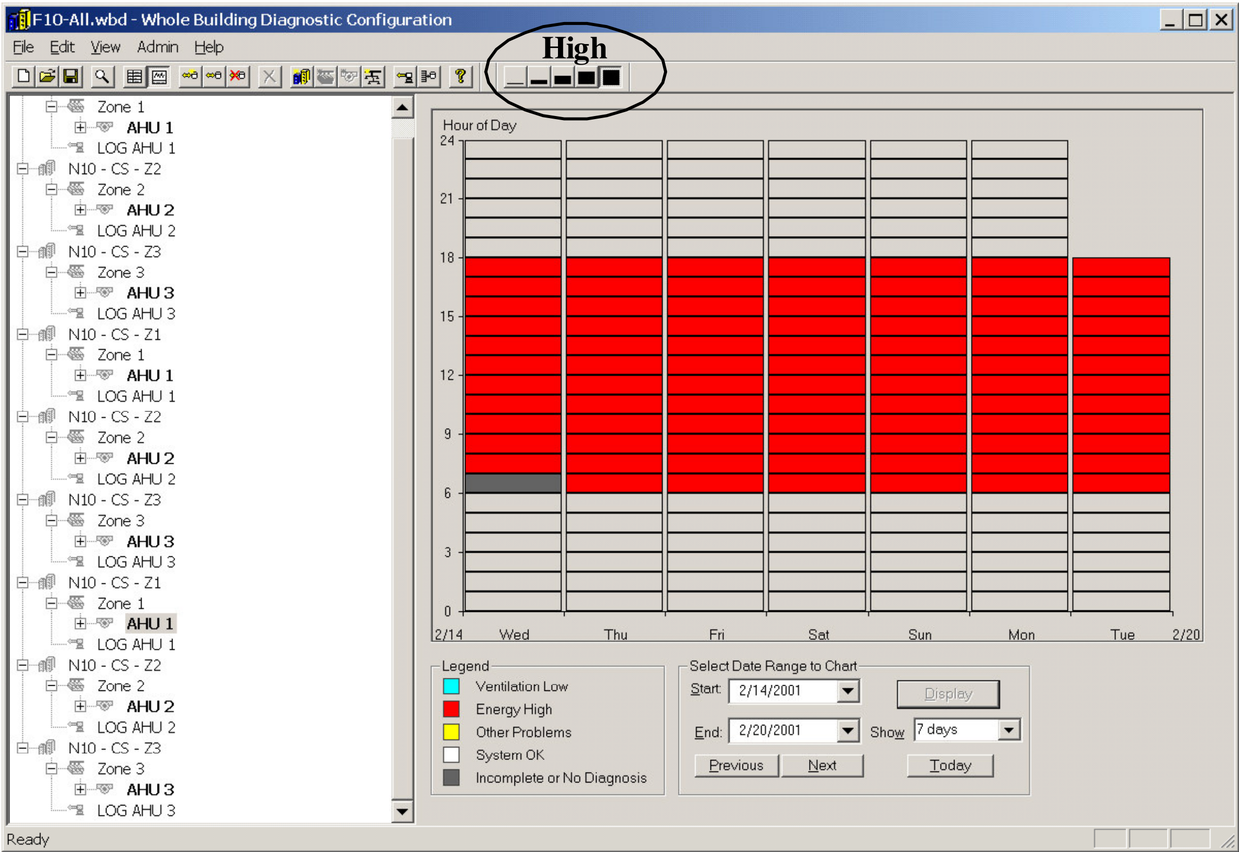


Figure 37)[3]. With the increased sensitivity, all cells (with the exception of one) during the occupied period are red, indicating higher than expected energy consumption. This finding is consistent with the fault induced. By clicking on a red cell, the current conditions, a list of potential causes, and suggested solutions can be obtained. Figure 38 shows the Current Conditions dialogue for February 20, 2001, at 4:00 p.m. The current condition as reported by the OAE is that the damper position signal is “OK” but the outdoor-air flow is too high, consistent with the fault instigated in the VCBT environment. Browsing through several other red cells reveals the same problem. The lists of possible causes do not explicitly indicate a problem with return-air damper. They do, however, point to the damper system failure. In addition, the detailed information clearly indicates the exact problem as shown in Figure 39.

[3] Note that increasing the fault-detection sensitivity creates a potential to increase the number of false alarms.

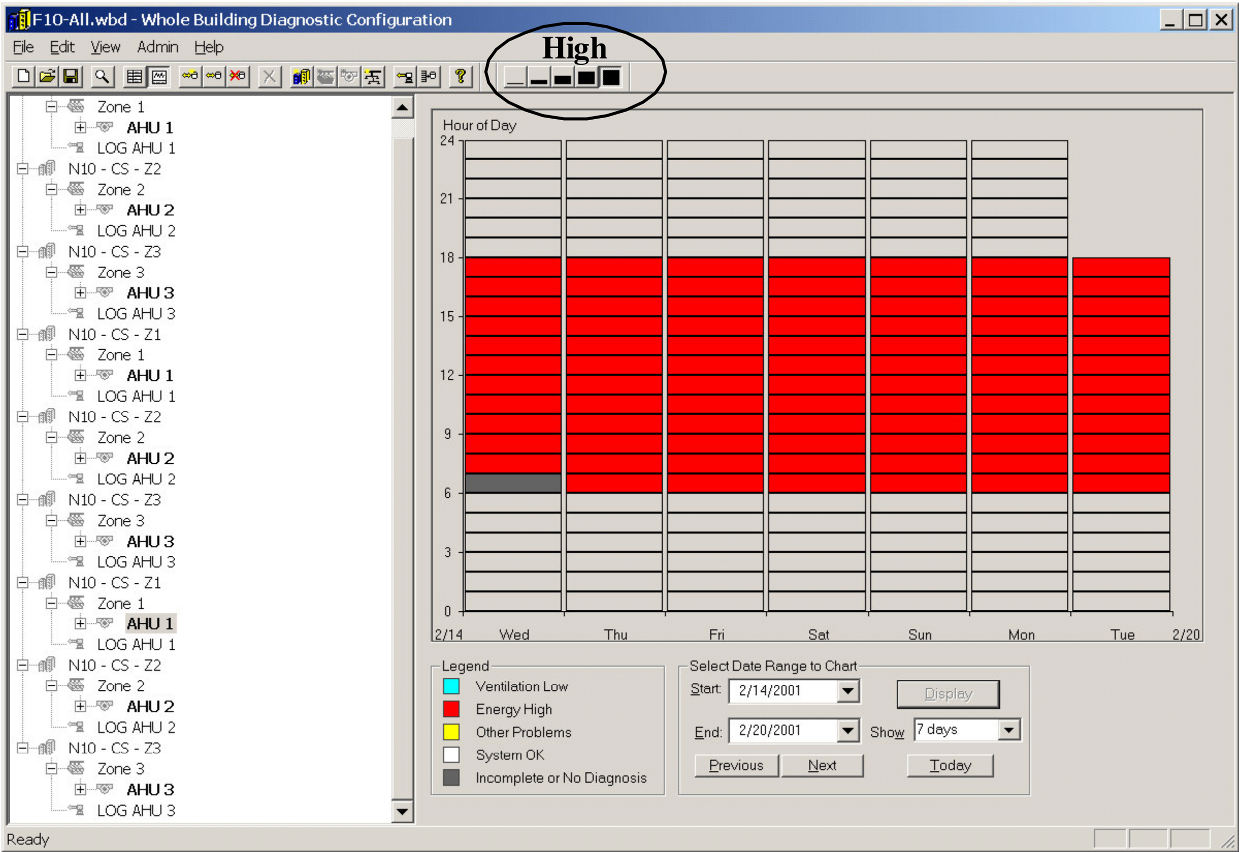


Figure 37 – OAE Diagnostic Results for AHU-1 with the Return-Air Damper Stuck in a Fully Closed Position for the High OAE Sensitivity Setting (data set Z1-CS-F10)

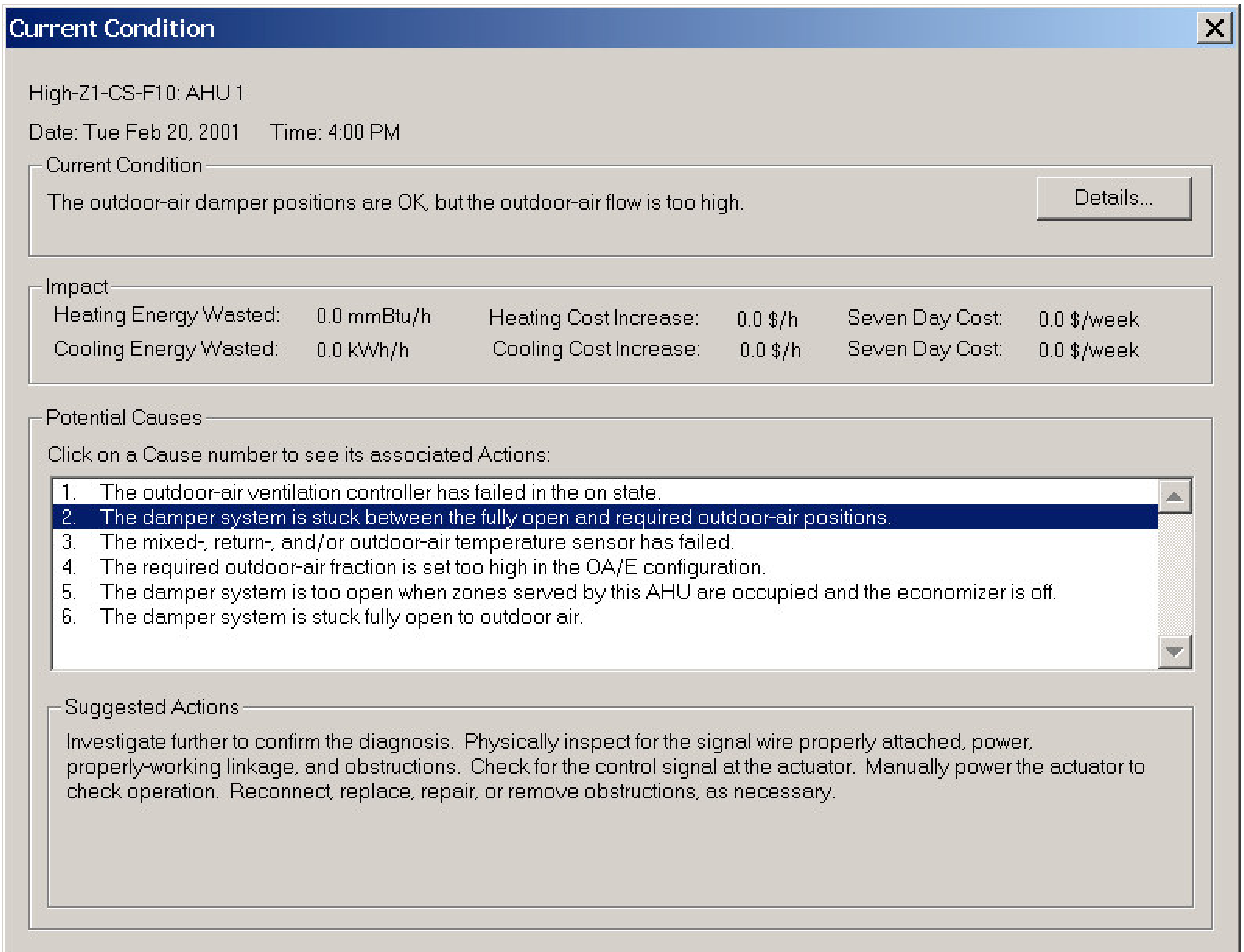


Figure 38 – Current Conditions Dialogue for AHU-1 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z1-CS-F10)

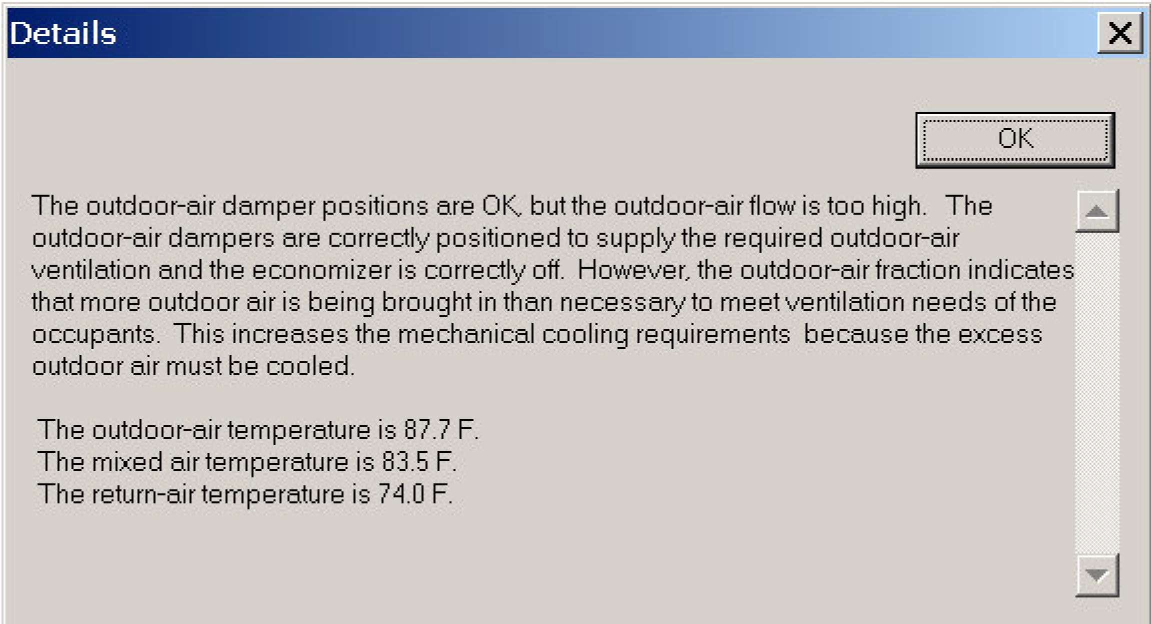


Figure 39 – Details Dialogue for AHU-1 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z1-CS-F10)

6.4.2 Faulty Economizer Control Logic (Z2-CS-F10)

The data set named Z2-CS-F10 was created using cooling season weather data and represents an AHU operation with faulty economizer control logic. The OAE diagnostic results for the Z2-CS-F10 data set are shown in Figure 40. This fault was introduced by reversing the logic used to decide whether the economizer or the minimum ventilation operation should become active. The supply-air temperature controller will still maintain the supply-air temperature set point under this condition. When the economizer logic is overridden to open the outdoor-air dampers more than the minimum when the conditions are not favorable for economizing, a fault occurs. Under these conditions, more outdoor air is drawn into the AHU, increasing the mechanical cooling requirements. This fault, unlike the previous one, was identified with the Normal sensitivity setting for the OAE.

Figure 41 shows the Current Conditions dialogue for February 20, 2001, at 4:00 p.m. The current condition, as reported by the OAE, is that the economizer should be off, but it is operating. This is consistent with the fault instigated in the VCBT environment. Several other red cells indicate the same problem. The fifth item in the list of potential causes corresponds to the instigated fault. Also, the detailed information clearly indicates the exact problem, as shown in Figure 42.

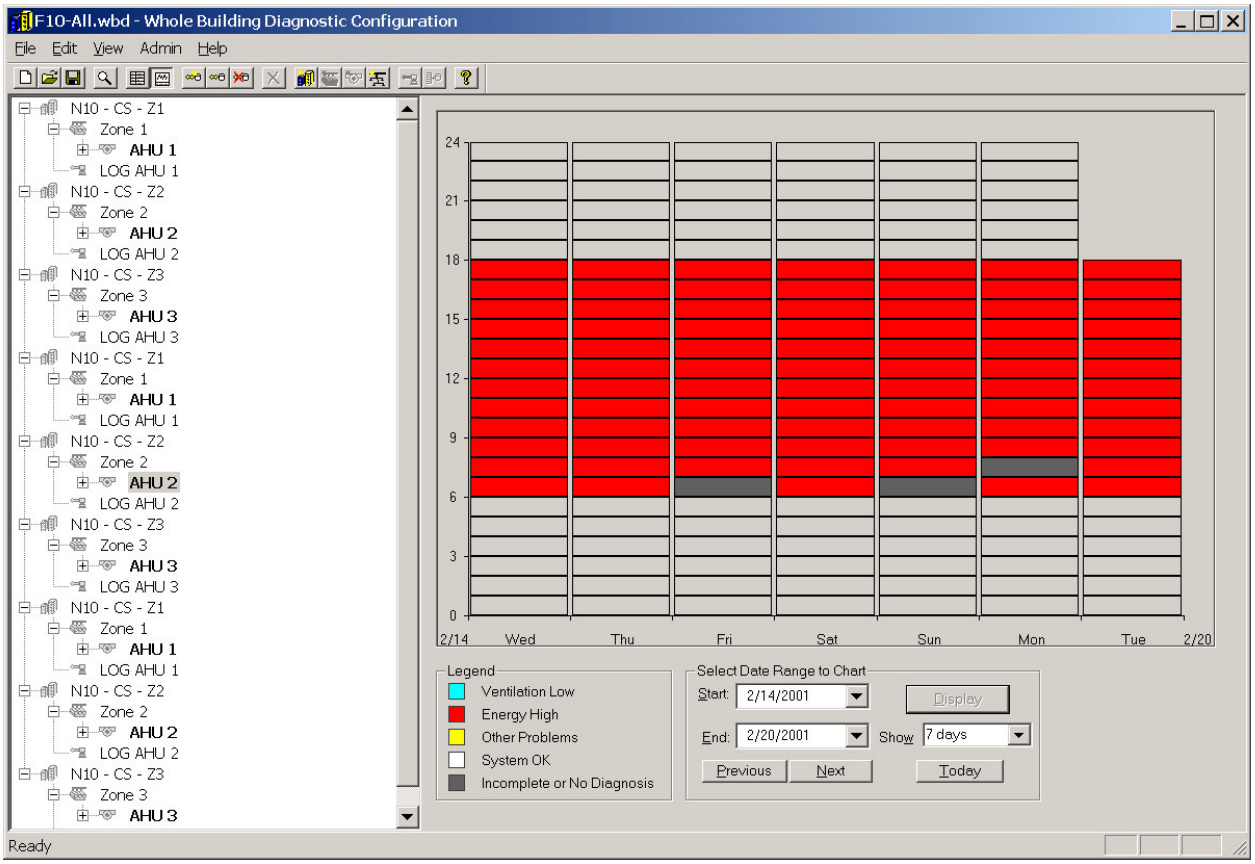


Figure 40 – OAE Diagnostic Results for AHU-2 with Faulty Economizer Control Logic for the Normal OAE Sensitivity Setting (data set Z2-CS-F10)

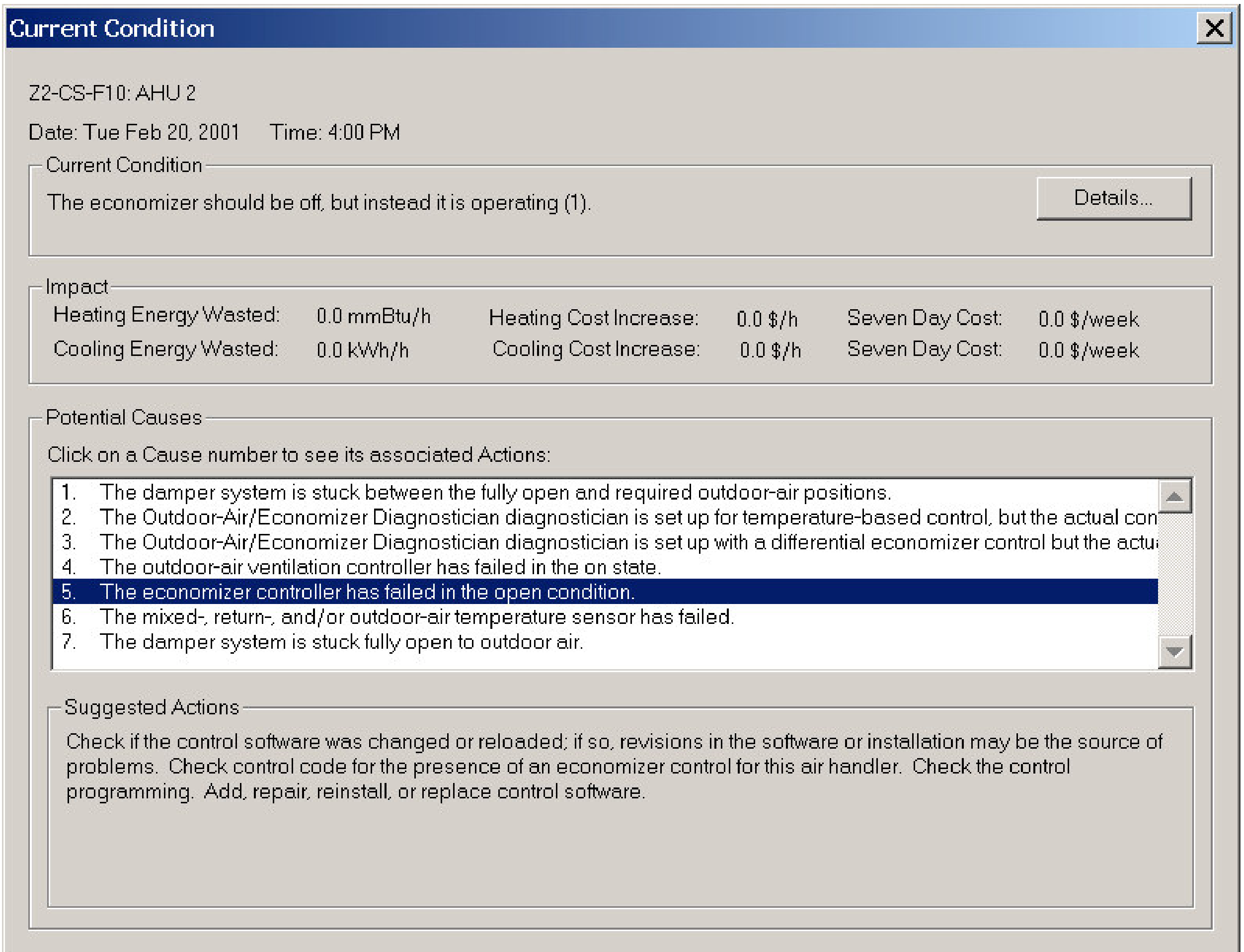


Figure 41 – Current Conditions Dialogue for AHU-2 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z2-CS-F10)

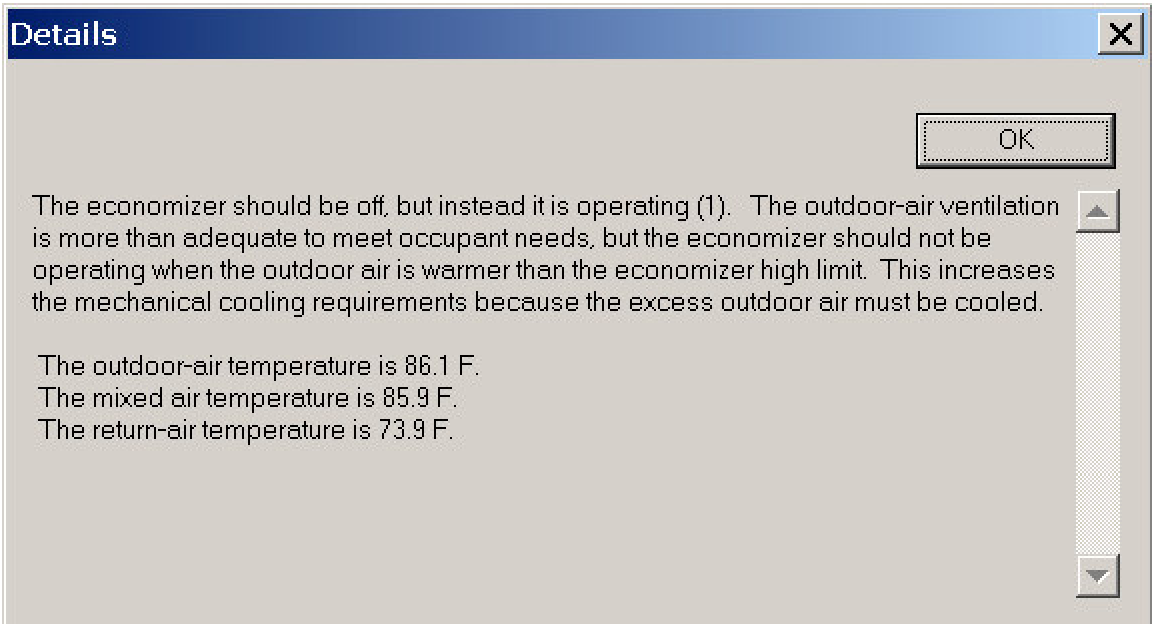


Figure 42 – Details Dialogue for AHU-2 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z2-CS-F10)

6.4.3 Drift in Mixed-Air Temperature Sensor (Z3-CS-F10)

The data set named Z3-CS-F10 was created using cooling season weather data and represents AHU operation with a faulty outdoor-air temperature sensor. The mixed-air temperature sensor drift was introduced as a sensor offset for a range of 0 to 7ºF, applied linearly over a 1-week emulation period.

The OAE diagnostics results for the Z3-CS-F10 data set are shown in Figure 43. The OAE diagnostician identified the fault immediately even with the Normal sensitivity setting. Figure 44 shows Current Conditions dialogue for February 20, 2001, at 4:00 p.m. The current condition as reported by the OAE is that a temperature sensor problem exists. This is consistent with the fault instigated in the VCBT environment. Browsing through several other cells also revealed the same problem. The single item in the list of potential causes corresponds to the instigated fault. Also, the detailed information clearly indicates the exact problem, as shown in Figure 45. Although the OAE identified a problem with a temperature sensor, it cannot distinguish which of the three sensors is faulty (mixed-, return- or outdoor-air temperature).

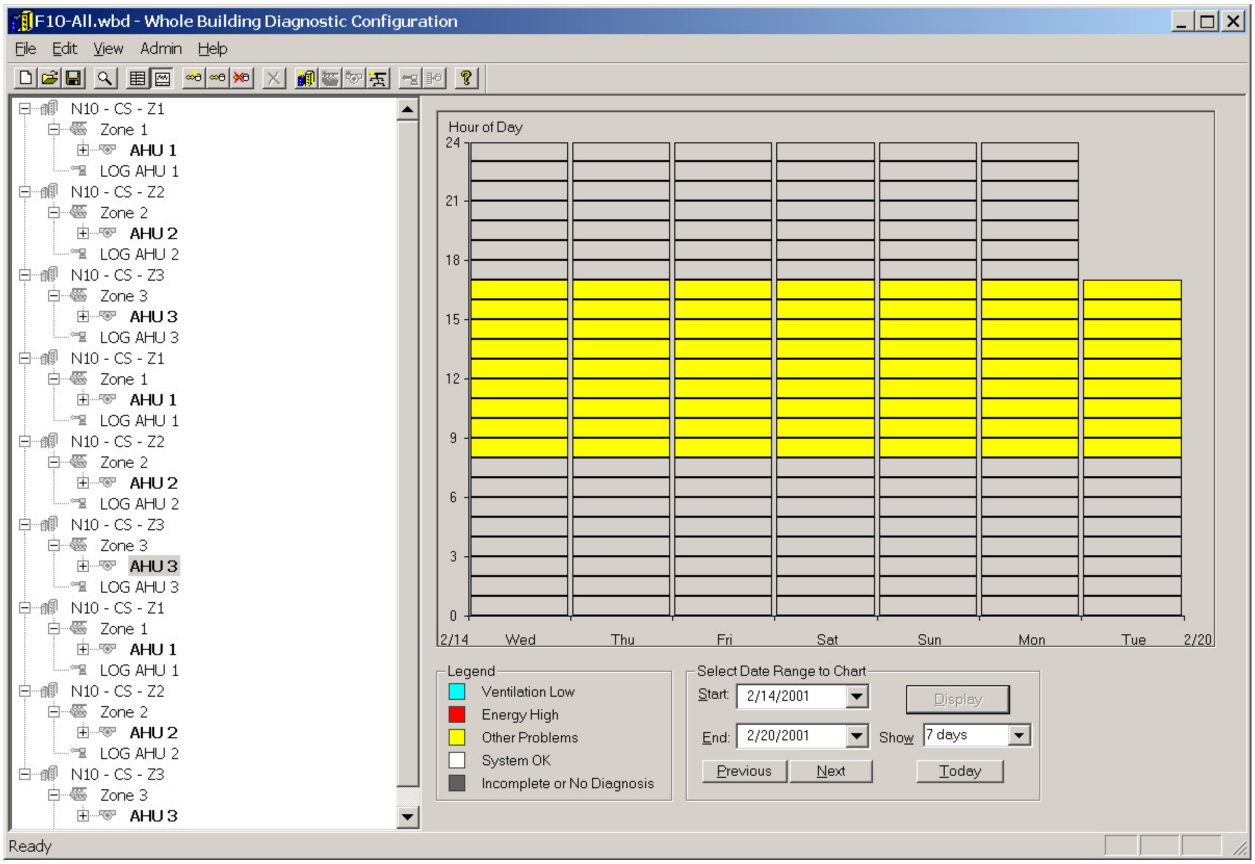


Figure 43 – OAE Diagnostic Results for AHU-3 with a Mixed-Air Temperature Sensor Problem for the Normal OAE Sensitivity Setting (data set Z3-CS-F10)

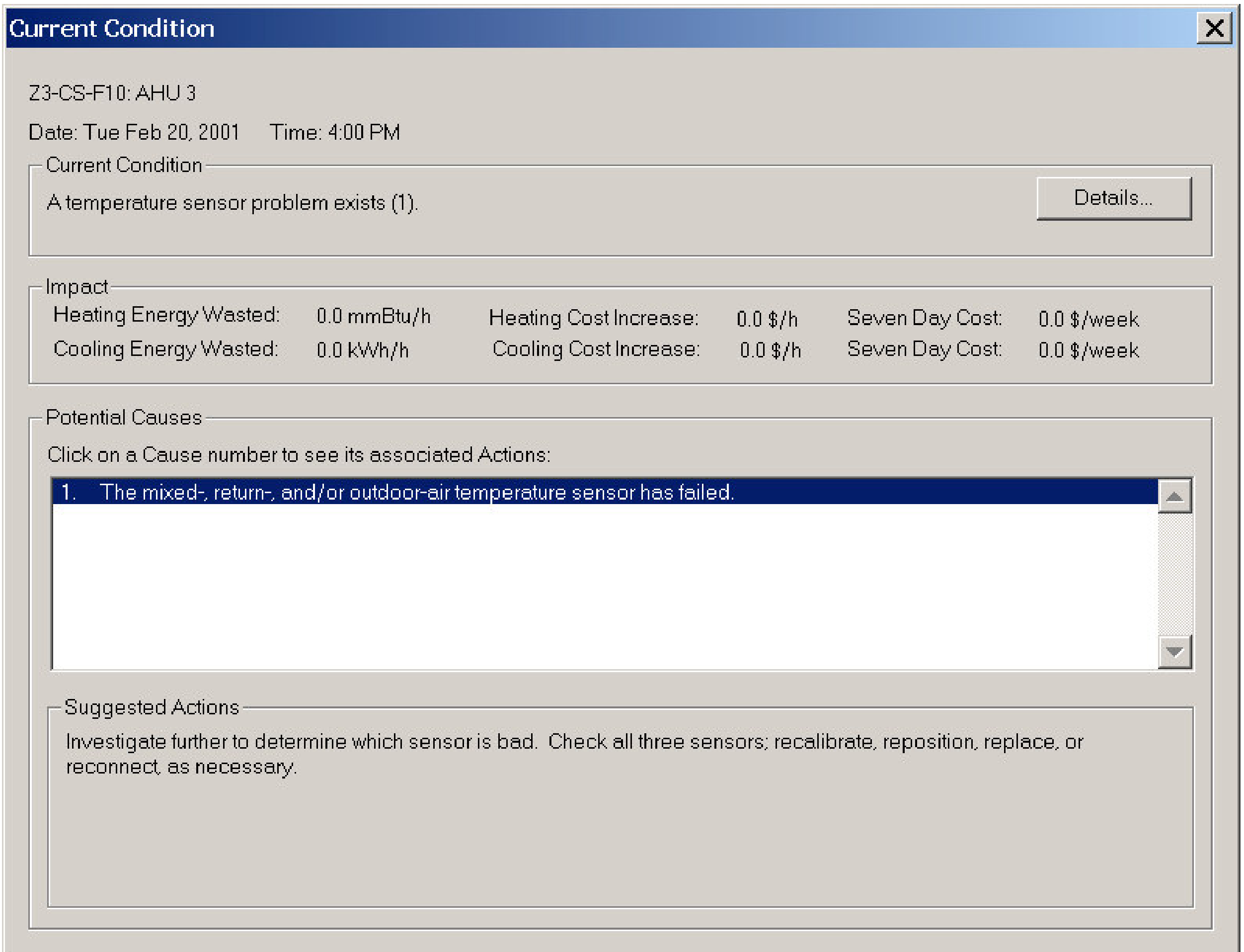


Figure 44 – Current Conditions Dialogue for AHU-3 on February 20, 2001, at 4:00 p.m. with a Mixed-Air Temperature Sensor Problem (data set Z3-CS-F10)

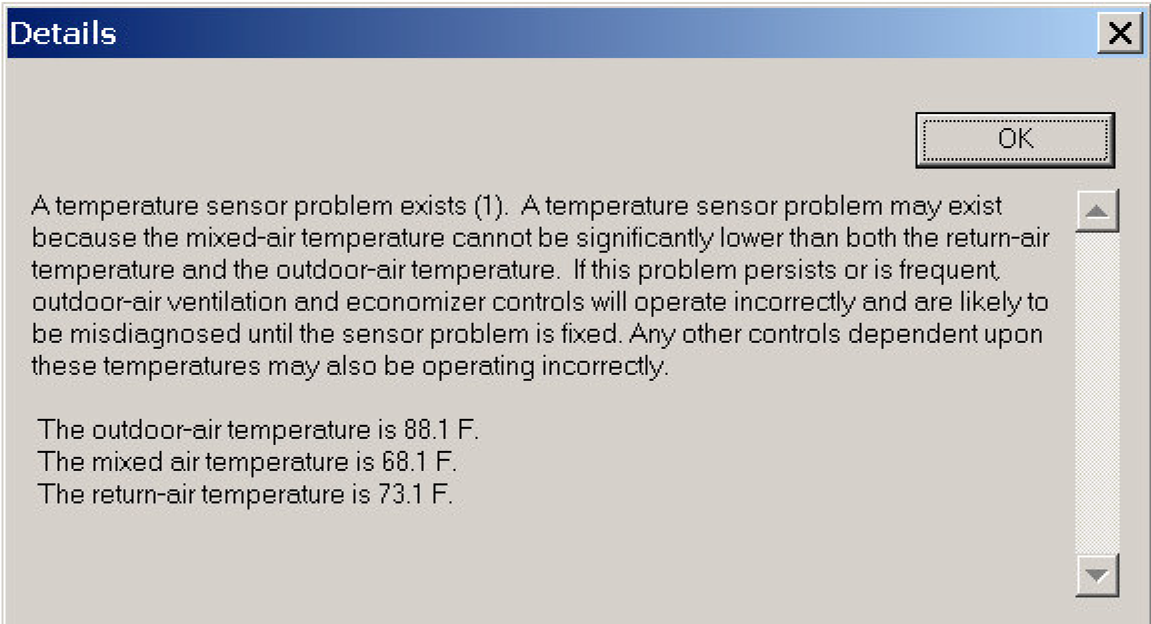


Figure 45 – Details Dialogue for AHU-3 on February 20, 2001, at 4:00 p.m. with a Mixed-Air Temperature Sensor Problem (data set Z3-CS-F10)

6.5 OAE Results from Blind Tests

To evaluate the diagnostic capability of the OAE diagnostician to detect faulty AHU operation, NIST generated 15 data sets for use in blind tests. Like the previous tests, all data sets start on the same date irrespective of the season being simulated, and they are at least 3 weeks long. The OAE diagnostic results from the blind test data sets are presented this section.

6.5.1 Data Set Z1-SS-F5A

The data set Z1-SS-F5A represents the first of the 15 blind data sets; it has three weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation used swing-season weather data. Figure 46 shows the screen shot of the OAE diagnostic results for this data set. With the exception of a few gray and white cells, most of the cells are red, which indicates an energy waste.

The Current Condition dialogue for 10:00 a.m. on February 3, 2001, is shown in Figure 47. The conditions for that particular hour indicate that the economizer should be operating fully open (i.e., the outdoor-air dampers), but it is only partially open. Although the OAE generates a list of potential causes for every fault, it displays them only if the certainty of the error is significant. In other words, if the OAE encounters the same problem over and over again, it becomes more and more certain of the problem and only then displays the list of potential causes for that problem. This implementation avoids false alarms when there are apparent transient problems (i.e., non-persistent random problems). Because the 10 a.m. hour on February 3, 2001, was the first occurrence of the problem, the OAE is not certain about the cause of the problem and, therefore, displays none.

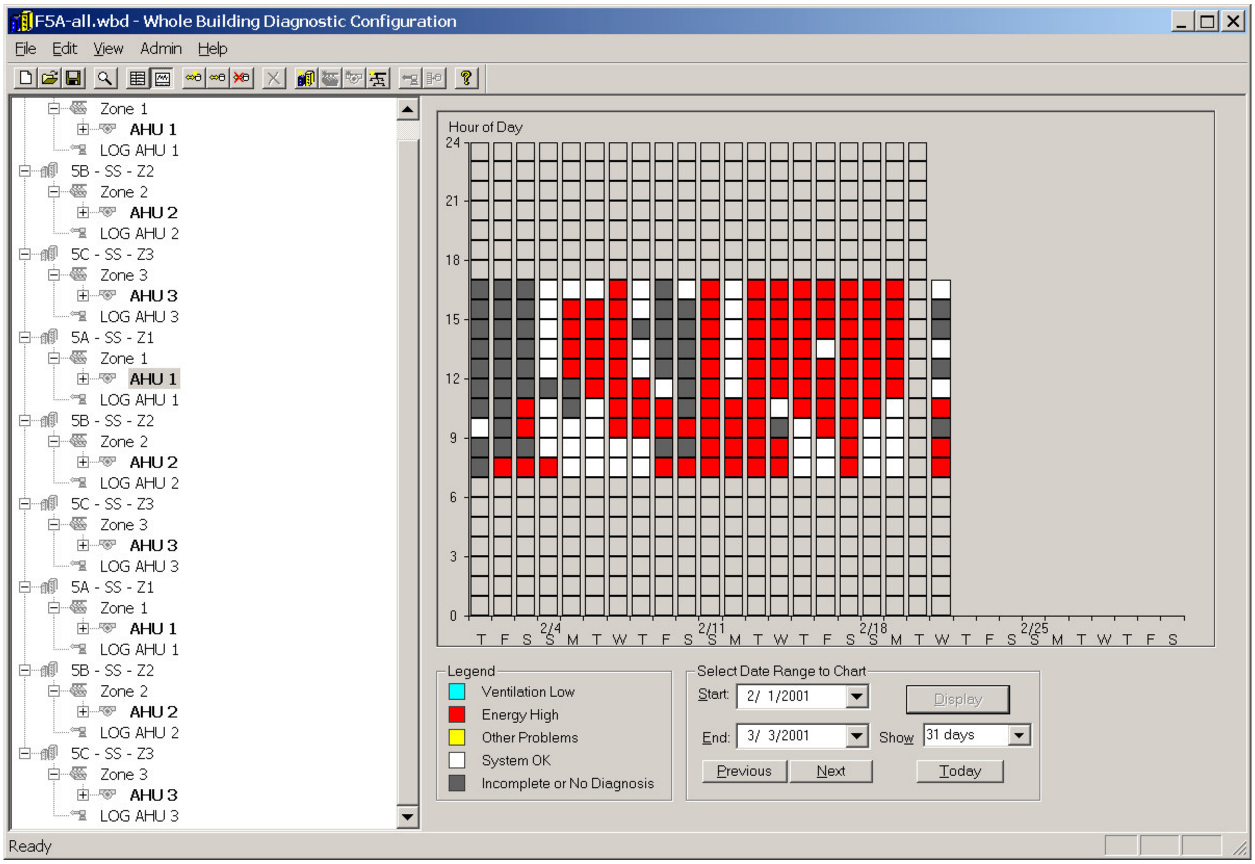


Figure 46 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-SS-F5A for a Swing Season with Normal OAE Sensitivity

The Current Conditions dialog for February 17, 2001, at 3:00 p.m. is shown in Figure 48. Between February 10th and February 17, there were a number of hours of faulty operation; therefore, the OAE became more certain of the fault and lists five possible potential causes. In some cases, depending on the nature of the fault, the list of potential causes reduces over time. However, in this case, the list of potential causes remained the same, even at the end of the simulation period (see Figure 49 and Figure 50).

Because the OAE was properly configured and setup, all causes related to the configuration can be eliminated (1, 3 and 4), which leaves causes 2 and 5. The temperature sensor fault is listed as a potential cause for many problems because it often cannot be ruled out completely. However, if there was a temperature sensor problem, there would be yellow cells. Therefore, it can be concluded that the most likely cause of the problem detected is potential cause number 2; the damper system fails to open completely indicating that the damper is stuck between its normal position (minimum ventilation) and fully open. Also, the order of the potential causes is important. In general, the cause that the OAE believes is most relevant is at the top of the list.

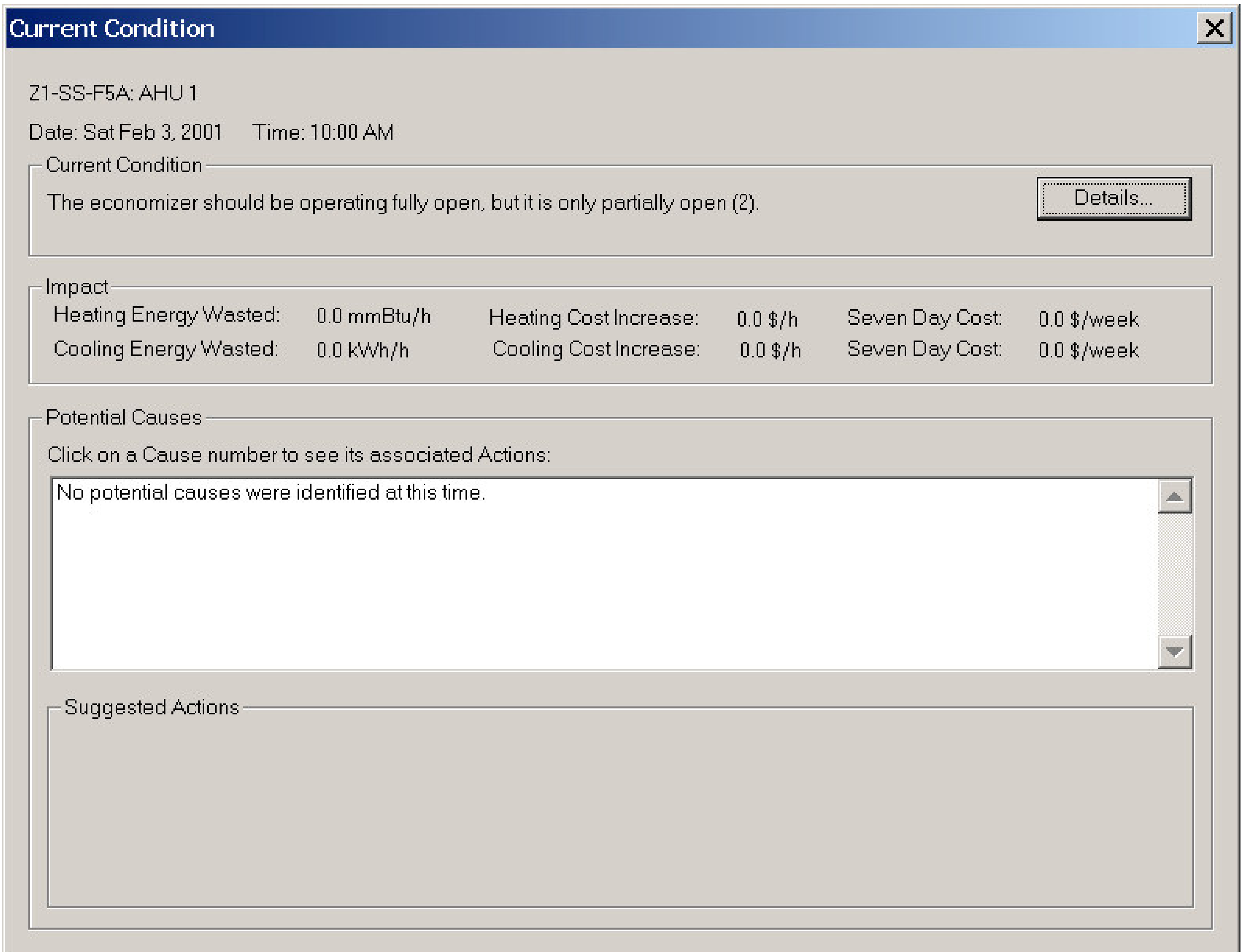


Figure 47 – Current Conditions Dialogue for AHU-1 on February 3, 2001, at 10:00 a.m. for Blind Test Data Set Z1-SS-F5A with Normal OAE Sensitivity

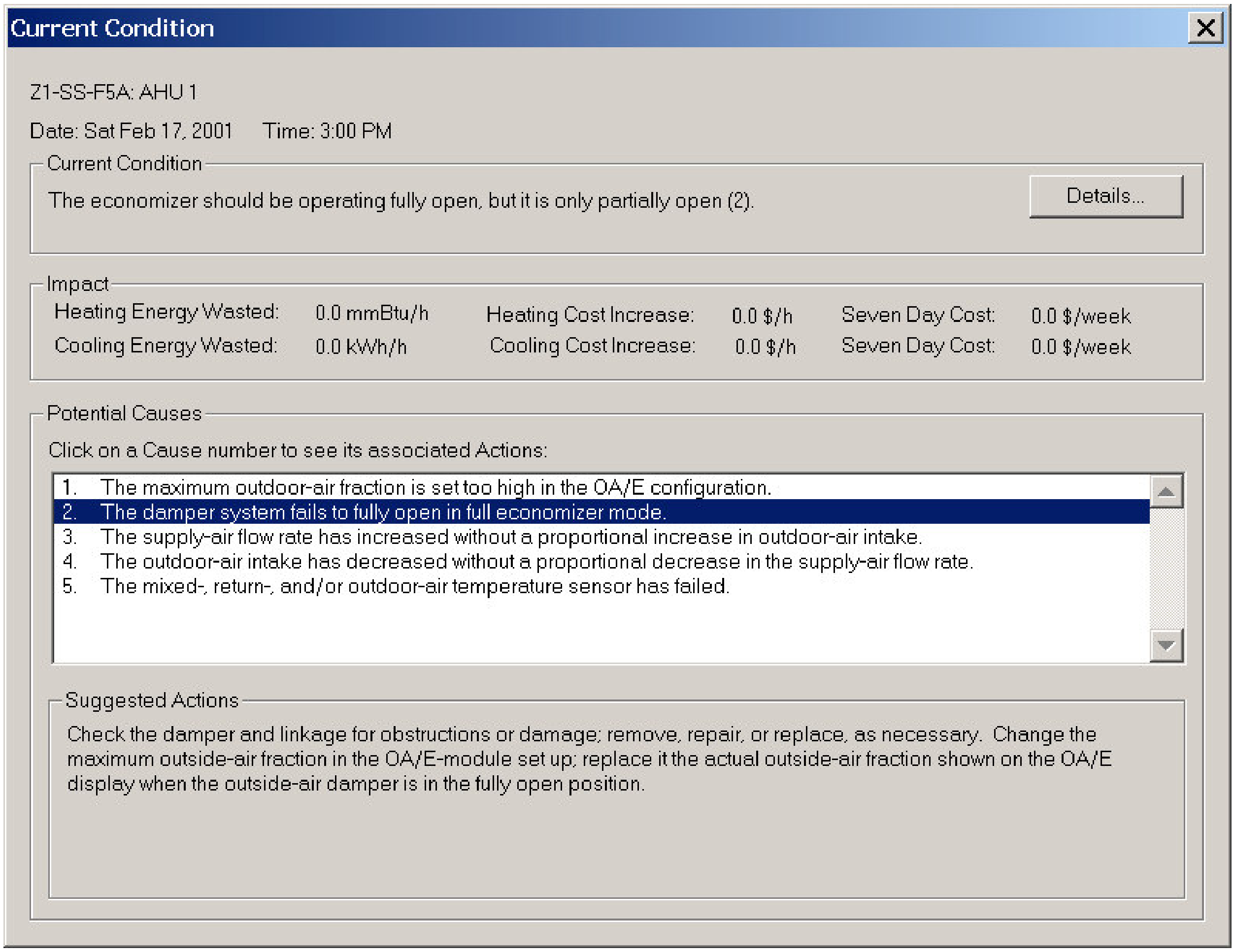


Figure 48 – Current Conditions Dialogue for AHU-1 on February 17, 2001, at 3:00 p.m. for Blind Test Data Set Z1-SS-F5A with Normal OAE Sensitivity

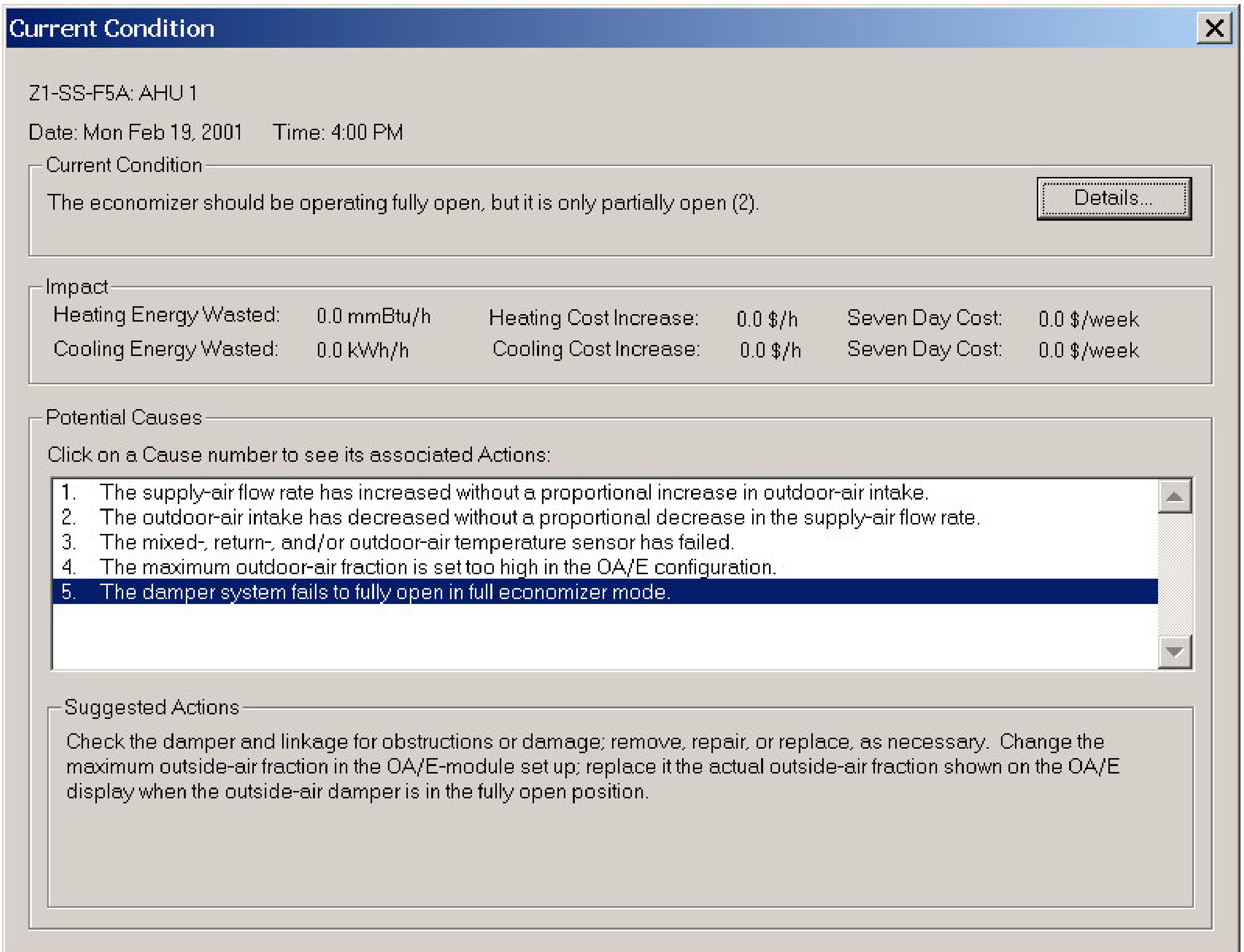


Figure 49 – Current Conditions Dialogue for AHU-1 on February 19, 2001, at 4:00 p.m. for Blind Test Data Set Z1-SS-F5A

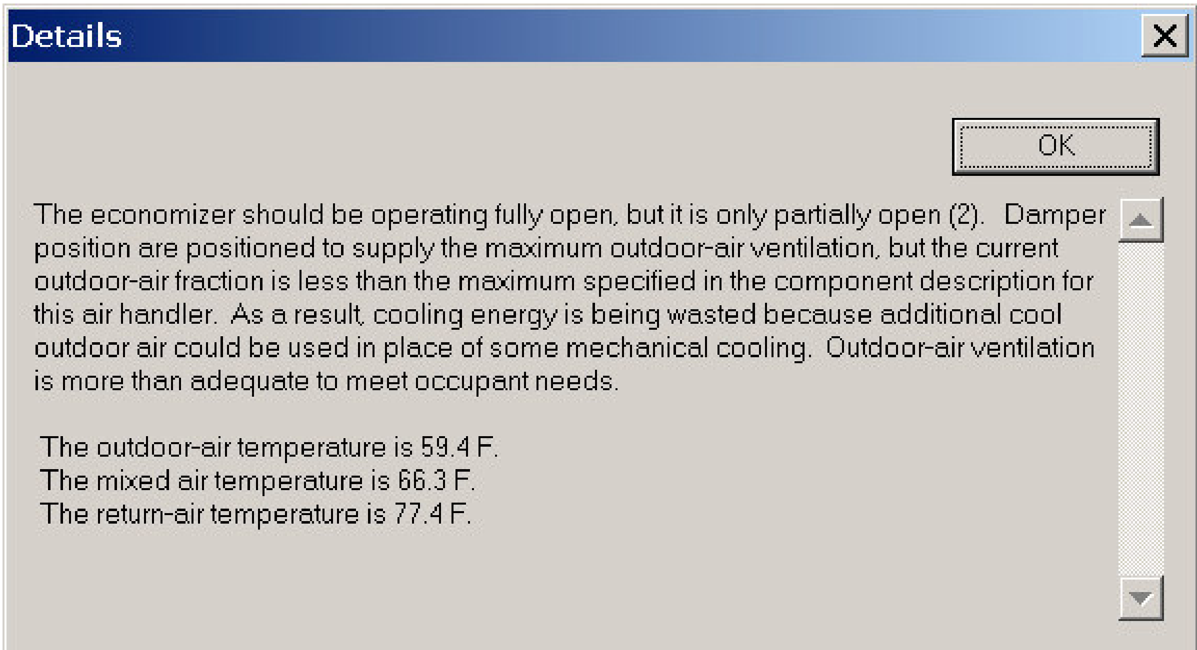


Figure 50 – Details Dialogue for AHU-1 on February 19, 2001, at 4:00 p.m. for Blind Data Set Z1-SS-F5A

The frequency of problems reported by the OAE in each major category, the corresponding reliability score and fraction of total hours in each category are shown in Table 3. The reliability score is the cumulative uncertainty calculated from propagating the measurement uncertainty through calculations done by the software. For Z1-SS-F5A test, almost 50% of the time AHU-1 was reporting to have “low economizer flow,” indicative of a stuck damper. The frequency analysis shown in Table 3 is not part of the WBD user interface. The information on which it is based comes from the display, as well as the OAE database. Advanced users could perform this analysis, but it is not a feature of the OAE currently.

For Z1-SS-F5A, both the OAE diagnostic results and the frequency analysis point to a damper that is stuck between its minimum and fully-open positions.

Table 3 – Frequency of the Problems for AHU-1 when the Building is Occupied (data set Z1-SS-F5A) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.717	5	2.5
Control Problem – Excess Energy		0	0.0
Excess Ventilation	0.869	1	0.5
Inadequate Ventilation		0	0.0
Low Economizer Flow	0.777	96	48.0
OK but incomplete	0.702	47	23.5
Operation OK	0.759	51	25.5
Total		200	100

6.5.2 Data Set Z2-SS-F5B

The data set Z2-SS-F5A has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on swing-season weather data. Figure 51 shows the screen shot of the OAE diagnostic results for this blind test data set. With the exception of a few gray and red cells, most cells are white, which indicates proper AHU operation. We recommend users ignore sporadic indications of operation problems and instead wait for the appearance of several sequential fault indictors or faults occurring in a repetitive pattern over time (e.g., at 1 p.m. on every week day).

Increasing the OAE detection sensitivity caused it to indicate a number of blue cells, as show in Figure 52. In general, blue cells indicate inadequate ventilation when the AHU is not economizing. The list of possible causes for this fault condition is shown in Figure 53. The most likely cause of the fault is either a temperature sensor problem or lack of adequate ventilation.

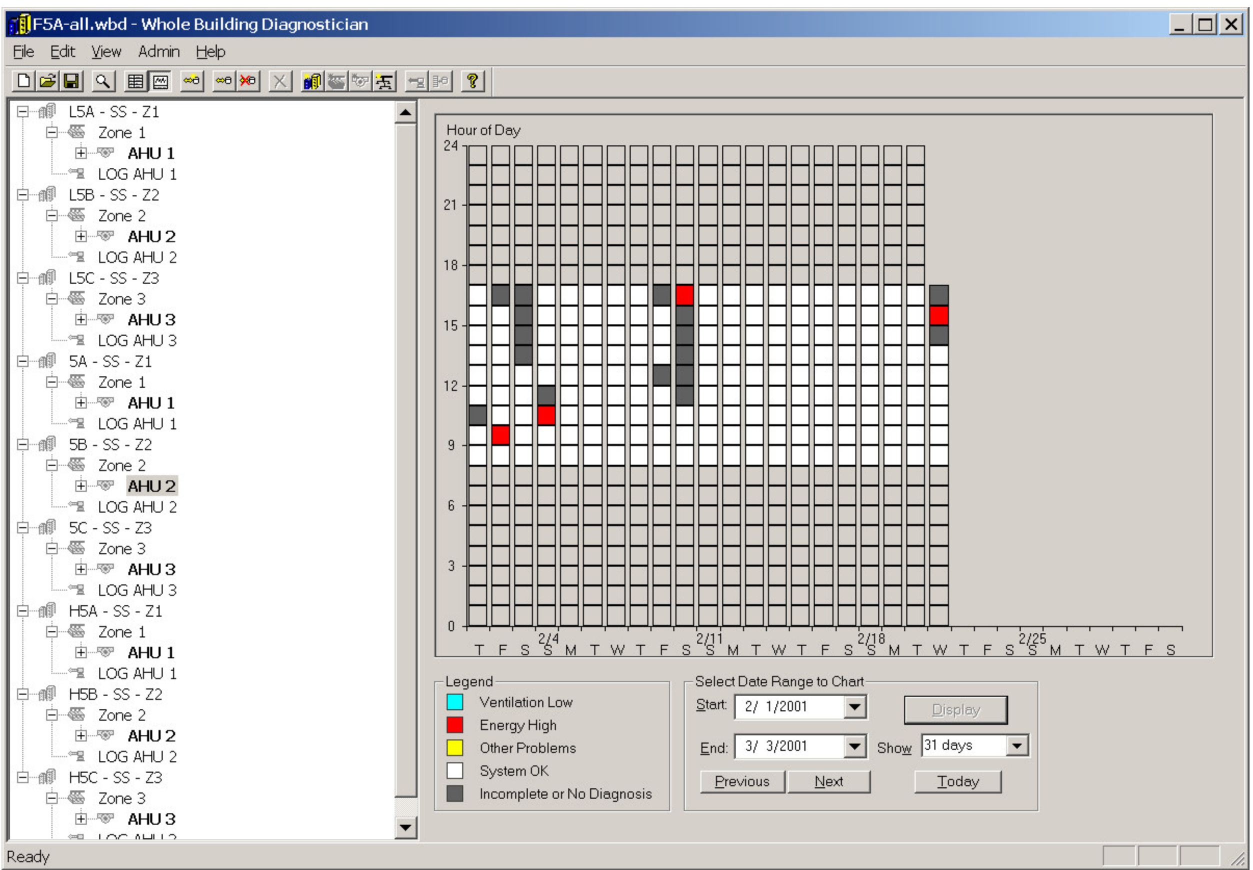


Figure 51 – OAE Diagnostic Results for AHU-2 with Blind Test Data Set Z2-SS-F5B for a Swing Season with Normal OAE Sensitivity

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total hours in each category are shown in Table 4. For Z2-SS-F5A test, almost 84% of the time, AHU-2 was reported to be operating properly and 10% of the time it showed inadequate ventilation.

For Z2-SS-F5B, the OAE using high sensitivity reported: 1) inadequate ventilation resulting from an outdoor-air damper problem during occupied hours while not economizing or 2) a temperature sensor problem. No problem was detected when the OAE was run at normal sensitivity.

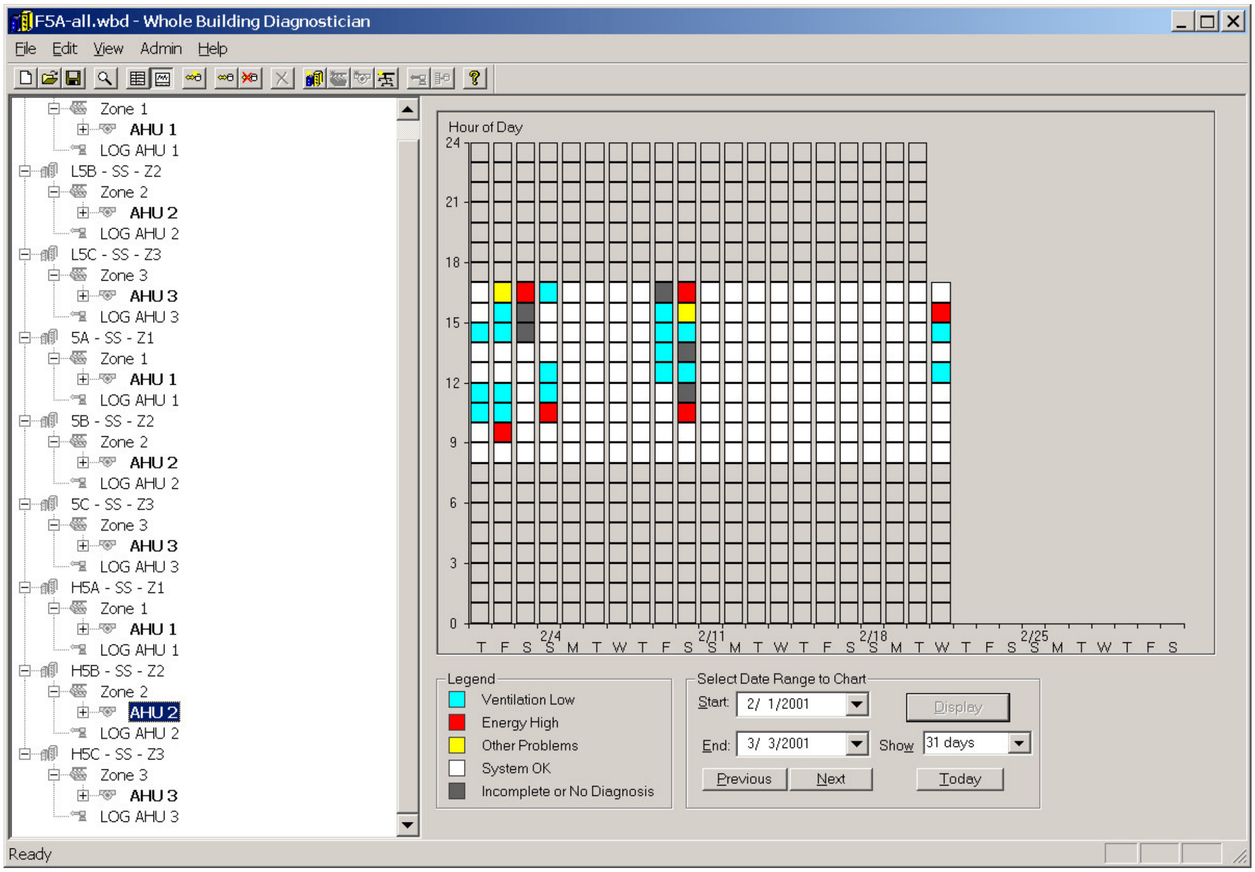


Figure 52 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-SS-F5B for a Swing Season with High OAE Sensitivity

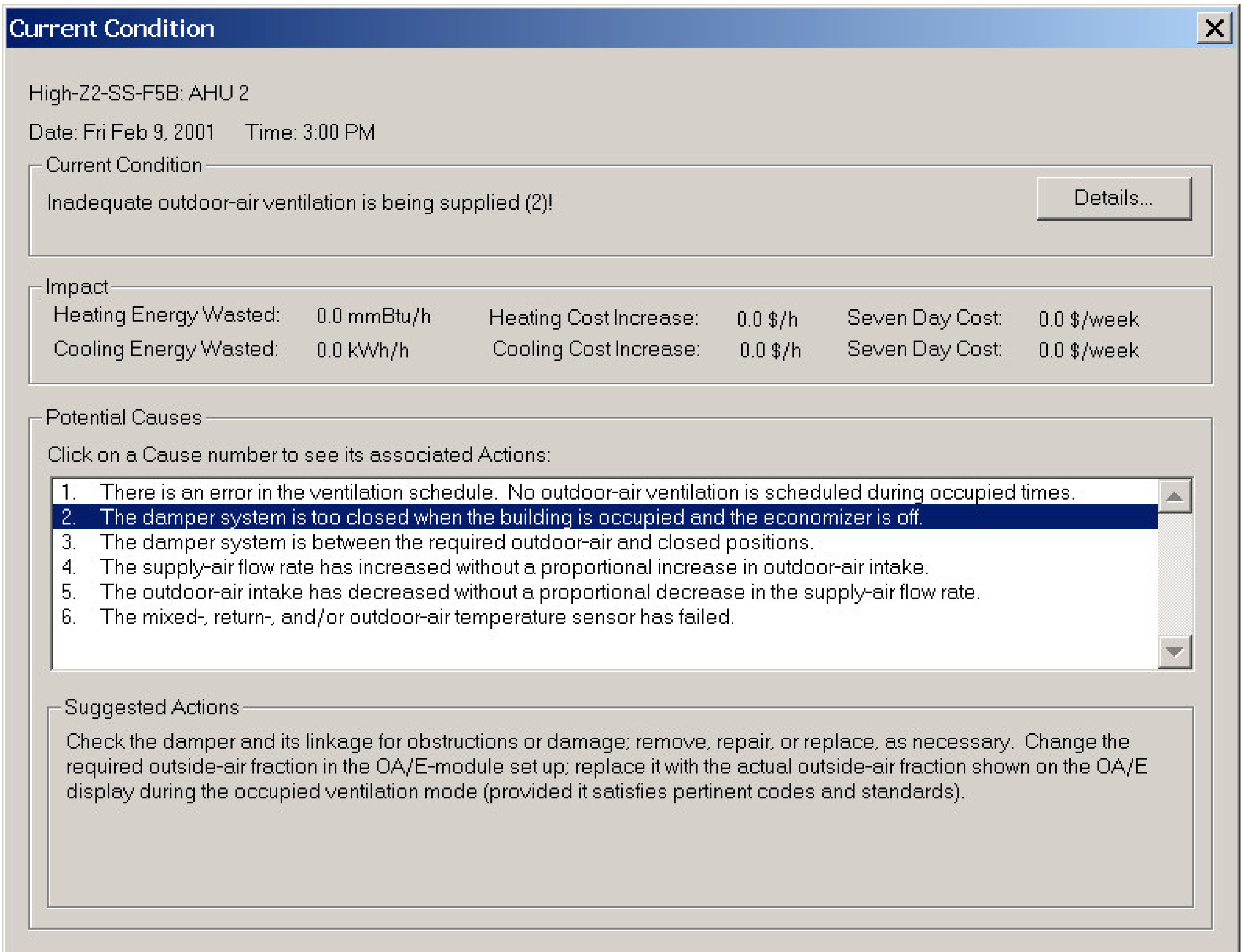


Figure 53 – Current Conditions Dialogue for AHU-2 on February 9, 2001, at 3:00 p.m. for Blind Test Data Set Z2-SS-F5B

Table 4 – Frequency of the Problems for AHU-1 when the Building is Occupied (Z1-SS-F5A) with Normal Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.909	2	1.1
Control Problem – Excess Energy		0	0.0
Excess Ventilation	0.924	1	0.5
Inadequate Ventilation	0.923	18	9.5
Low Economizer Flow	0.878	5	2.6
OK but incomplete	0.958	5	2.6
Operation OK	0.569	158	83.6
Total		189	100.0

6.5.3 Data Set Z3-SS-F5C

The data set named Z3-SS-F5A has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on swing-season weather data. Figure 54 shows the screen shot of the OAE diagnostic results for this data set with the OAE set at normal sensitivity. With the exception of a few gray cells, most of the cells are white, which indicates proper operation. Increasing the OAE detection sensitivity introduced a few blue and yellow cells (see Figure 55).

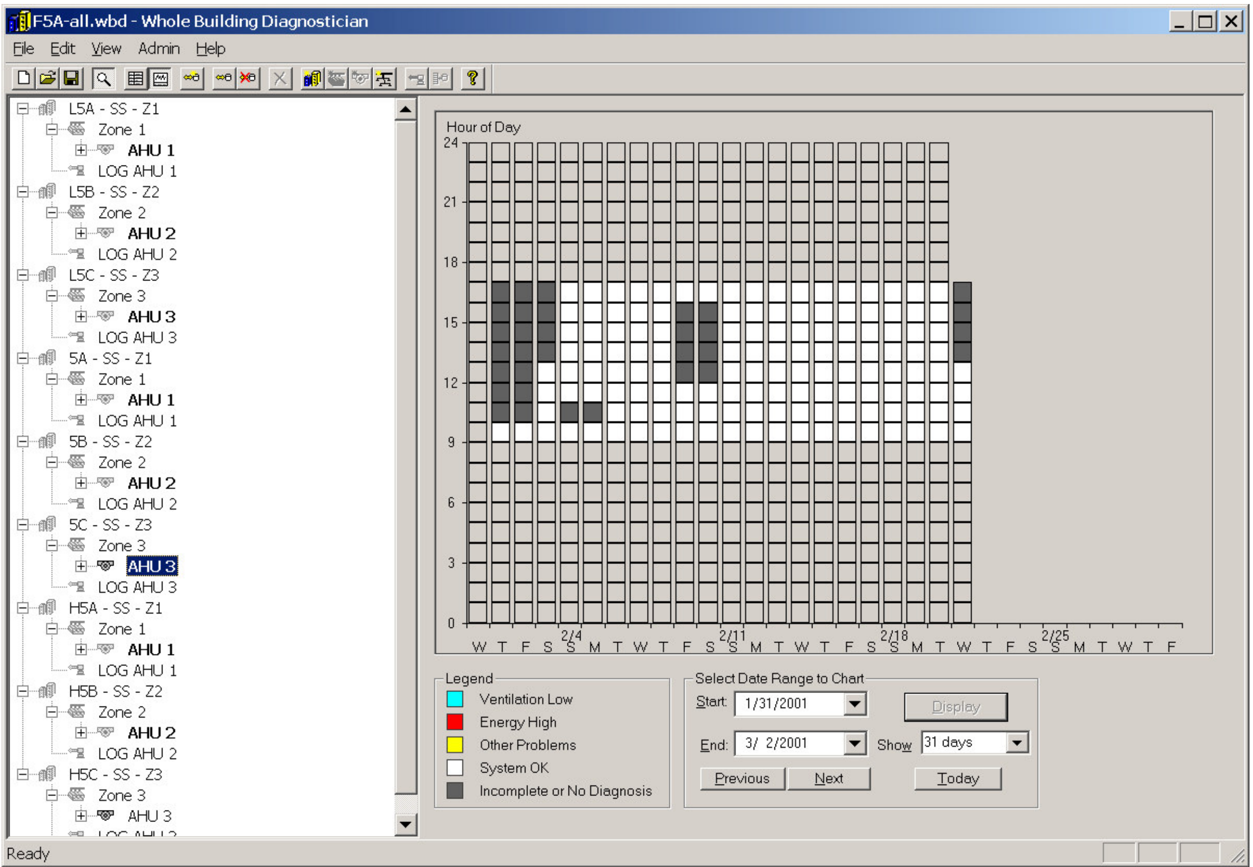


Figure 54 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F5C for Swing Season Weather with Normal OAE Sensitivity

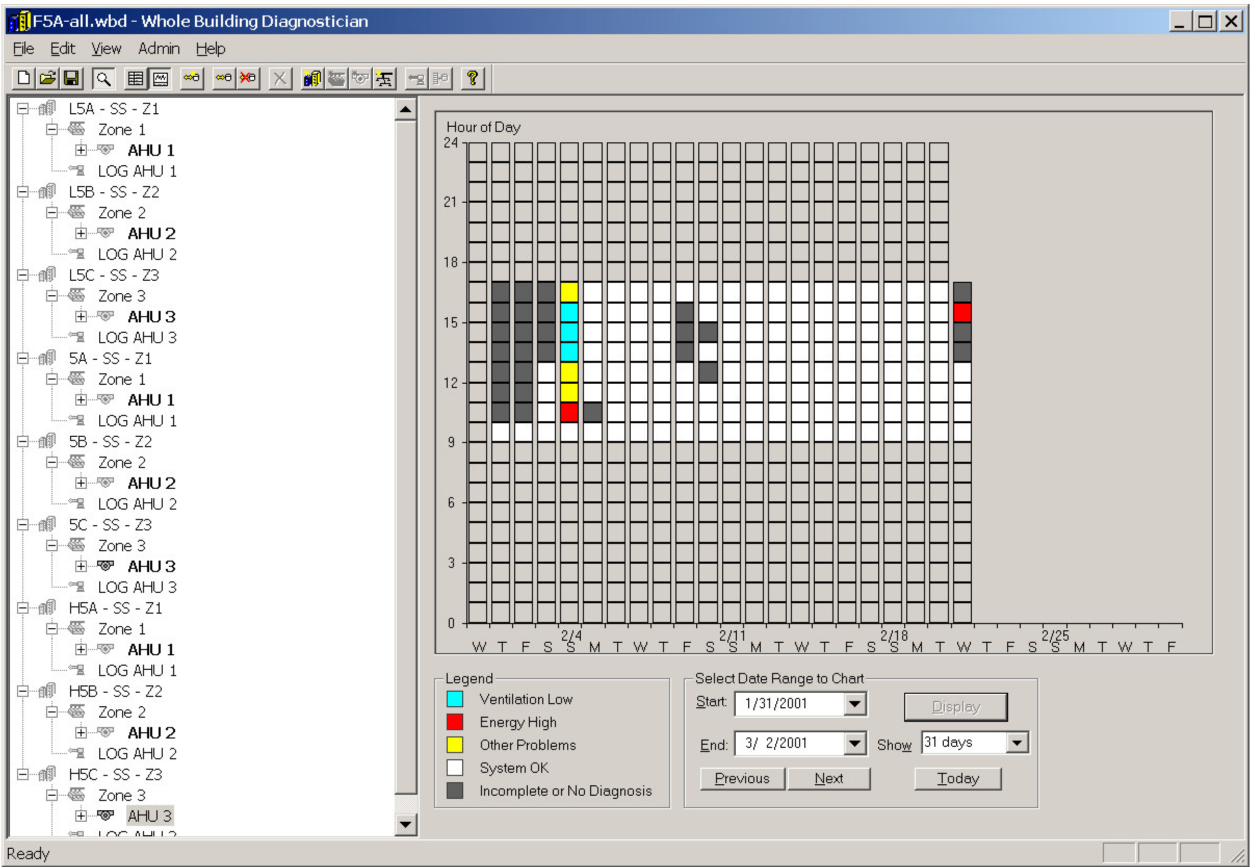


Figure 55 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F5C for Swing Season Weather with High OAE Sensitivity

Further manual analysis indicates that the data set had a return-air temperature sensor that was drifting over the 3-week period, as shown in Figure 56, but the OAE did not detect it. The OAE diagnostician did not detect this drift because conditions during the test made it impossible for the fault to manifest. However, if the problem continued into the summer season, it would have manifested for several hours and thereby provided a basis for detection. For example, on February 4, 2001, the outdoor-air conditions were such that the problem did manifest (Figure 55) for most of the day (7 hours). After February 4, conditions were not favorable for the fault to manifest again. When there are no errors in the measurement of the outdoor-air and the mixed-air temperatures, and the measured outdoor-air temperature is greater than the actual return-air temperature, then a positive bias in the measured return-air temperature (including drift to this state) will be detected when the measured return-air temperature exceeds the measured mixed-air temperature (which is equal to the actual mixed-air temperature because there is no error in the mixed-air temperature measurement for this fault). Under these conditions the measured mixed-air temperature will be less than both the measured outdoor- and return-air temperatures.

In this test data set, however, this condition occurred only for a few hours out of the entire 3-week period. The same fault during the summer season, when the outdoor-air temperature is greater than the return-air temperature most of the time, was detected by the OAE (refer to blind test fault Z3-CS-F9 described later in this section). This fault has little consequence during swing-season weather and, therefore, the consequence of the OAE not detecting it is minor. Therefore, when the fault has significant consequences (e.g., in summer), the OAE will detect it.

For Z3-SS-F5C, the OAE diagnostic results indicated that no significant faults occurred. A temperature sensor was drifting but outdoor conditions were not favorable for the fault to manifest and the OAE to detect it.

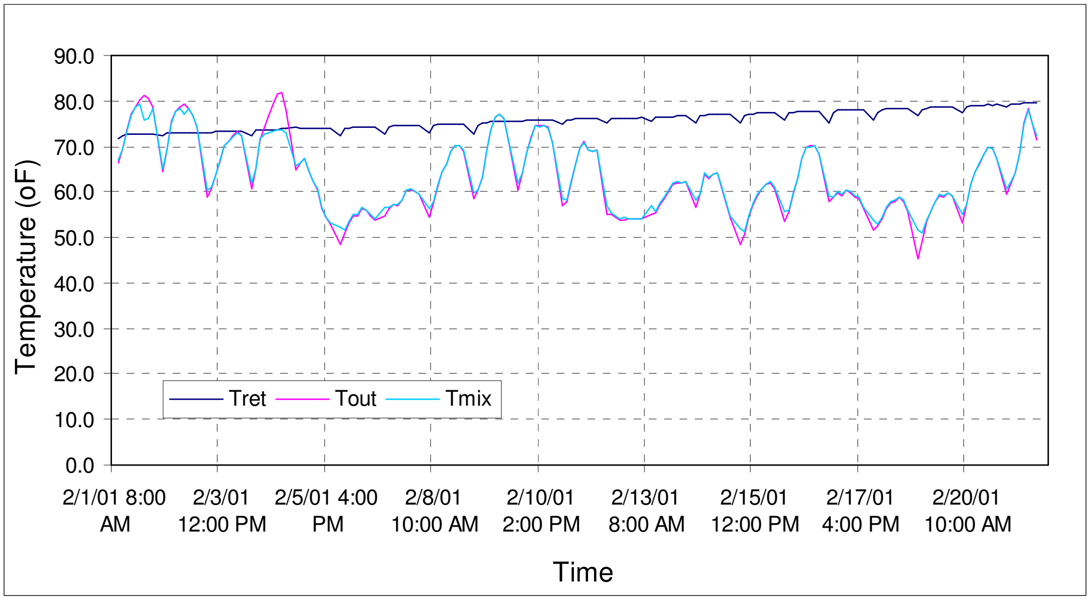


Figure 56 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z3-SS-F5C

6.5.4 Data Set Z1-HS-F4

The data set Z1-HS-F4 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on heating-season weather data. Figure 57 shows the screen shot of the OAE diagnostic results for this data set for normal OAE sensitivity. With the exception of a few red cells, most cells are white, which indicates proper operation. Increasing the OAE sensitivity did not change the results significantly.

Further manual analysis indicates that the data set had a mixed-air temperature that was drifting over the 3-week period as shown in Figure 58, but the OAE did not detect it.

For Z1-HS-F4, the OAE diagnostic results indicated that no significant faults occurred.

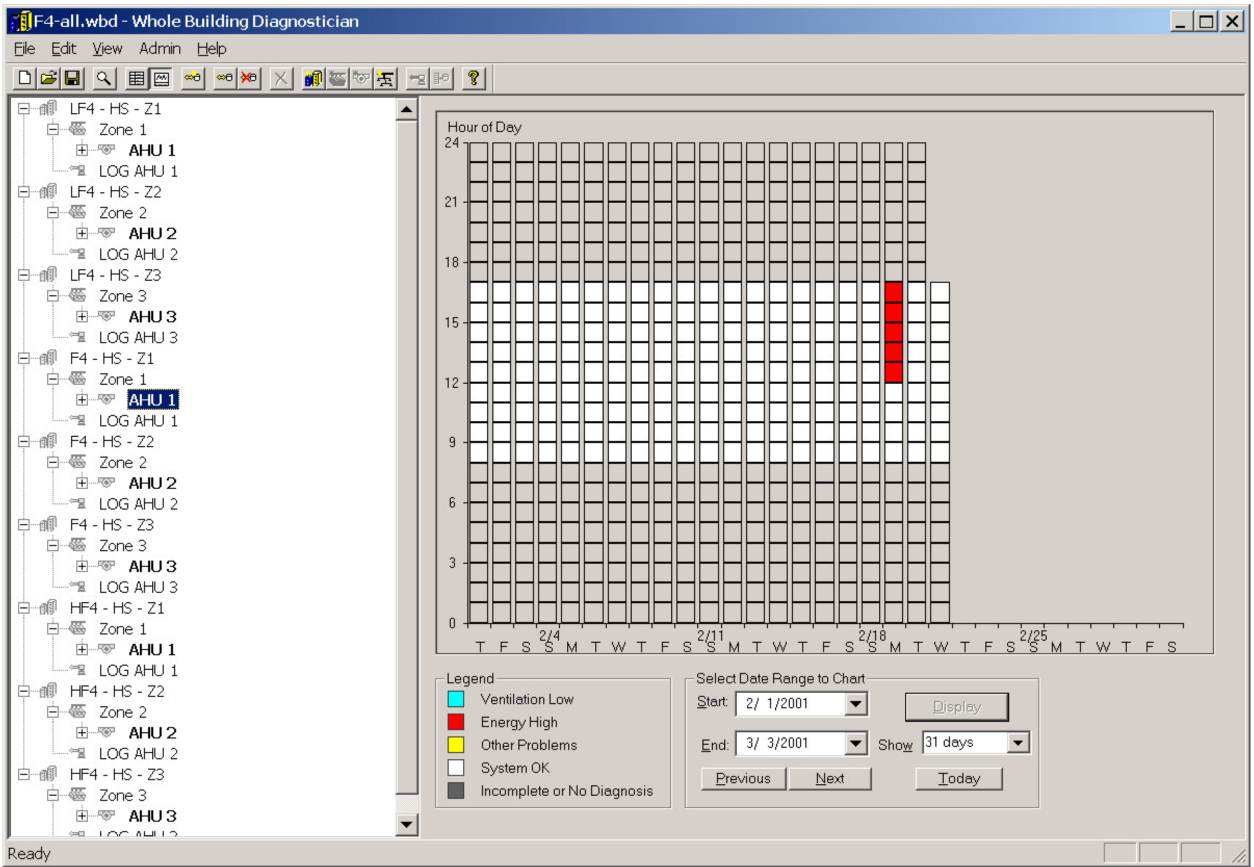


Figure 57 – OAE Diagnostic Results for AHU-1 with Blind Test Data Set Z1-HS-F4 for Heating-Season Weather with Normal OAE Sensitivity

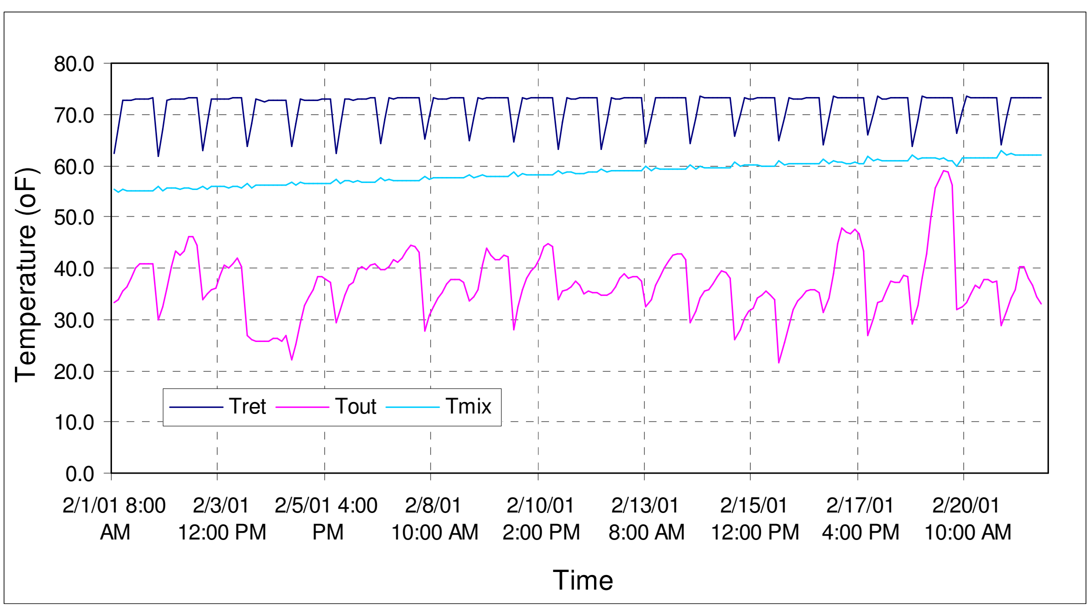


Figure 58 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z1-SS-F4

6.5.5 Data set Z2-HS-F4

The data set Z2-SS-F4 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on heating-season weather data. Figure 59 shows the screen shot of the OAE diagnostic results for this data set for normal OAE sensitivity. All cells are white, indicating proper operation. Increasing the sensitivity did not change the results.

For Z2-HS-F4, the OAE diagnostic results reported normal operations without faults.

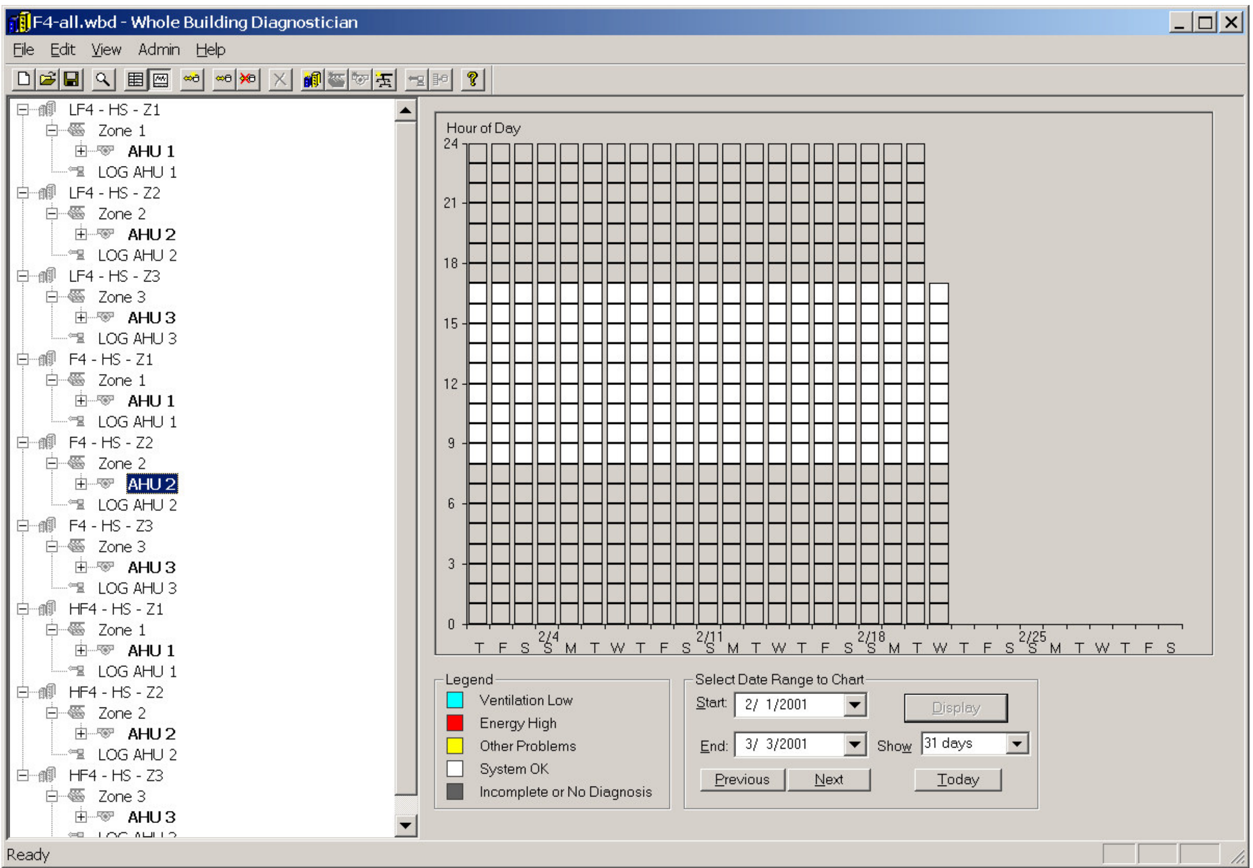


Figure 59 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-HS-F4 for Heating Season Weather with Normal OE Sensitivity

6.5.6 Data Set Z3-HS-F4

The data set Z3-SS-F4 has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on heating-season weather data. Figure 60 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few white cells, most cells are yellow, indicating a problem in the other problem category (which usually is a temperature-sensor problem).

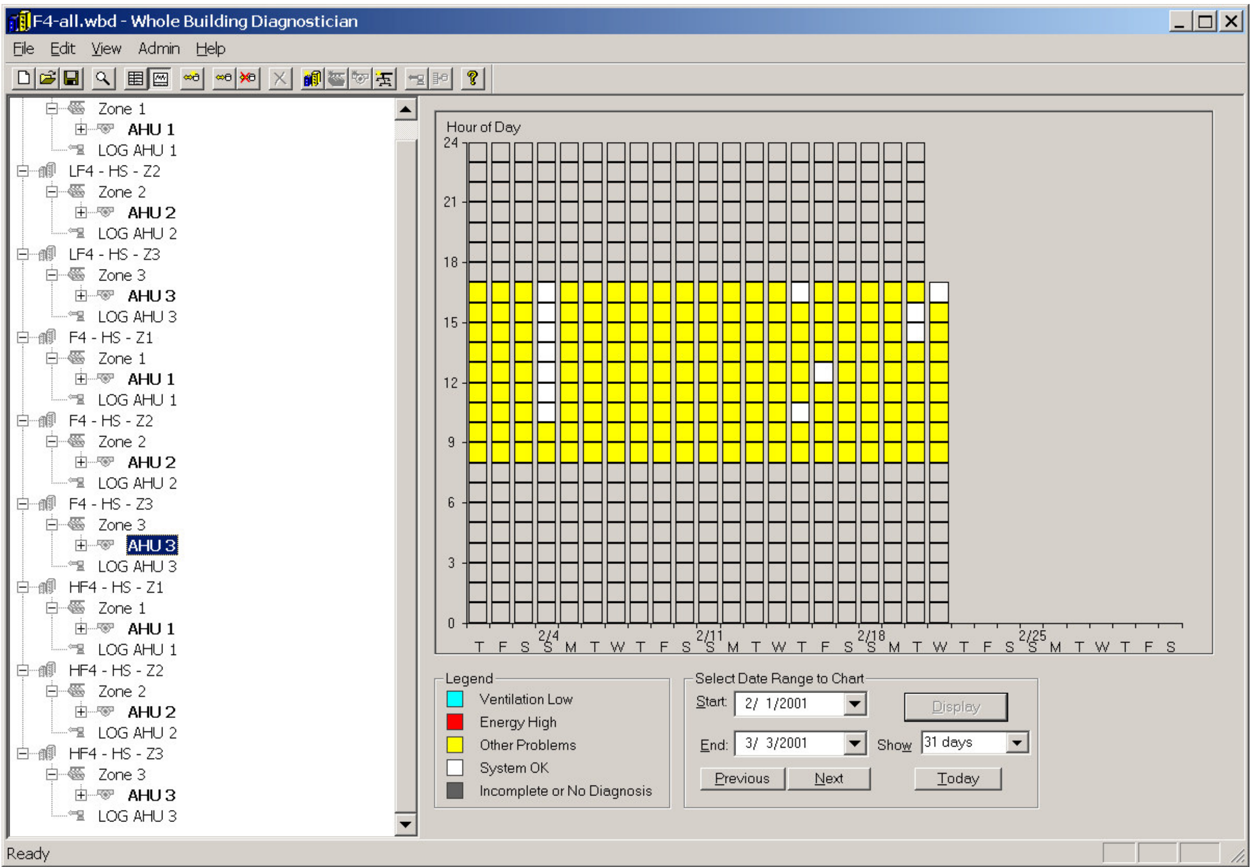


Figure 60 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-HS-F4 for Heating Season Weather with Normal OAE Sensitivity

The Current Condition and Details dialogue for 3:00 p.m. on February 15, 2001, is shown in Figure 61 and Figure 62, respectively. The conditions for that hour indicate a temperature sensor problem. The list of potential causes has just one cause, indicating that at least one of the three temperature sensors is faulty (outdoor-, mixed-, or return-air). Because the OAE diagnostician relies on minimum measured data, there is a lack of redundancy to isolate the faulty sensor. However, once the fault is detected, the operator can easily isolate the faulty sensor by checking the three sensors.

The frequency of problems reported by OAE in each major category, the corresponding reliability score, and fraction of total hours in each category are shown in Table 5. For the Z1-HS-F4 test, the OAE reported "Other Problems" 93% of the time, indicative of a temperature sensor problem.

Further manual analysis indicates that the return-air temperature is normal because it is in the expected range; therefore, the mixed-air or the outdoor-air temperature sensor is faulty (Figure 63).

For Z3-HS-F4, both the OAE diagnostic results and the frequency analysis point to a temperature sensor problem.

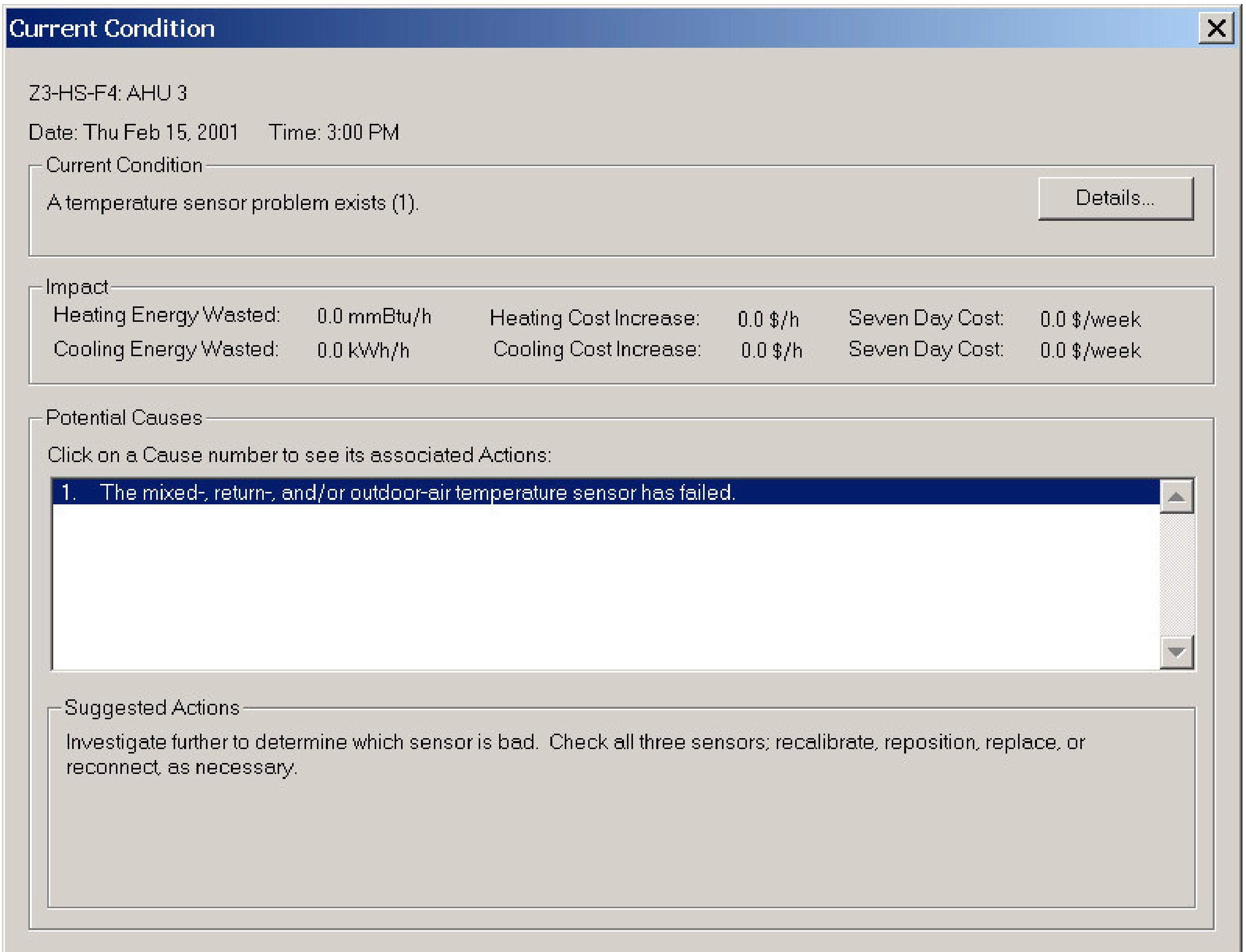


Figure 61 – Current Conditions Dialogue for AHU-3 on February 15, 2001, at 3:00 p.m. for Blind Test Data Set Z3-HS-F4

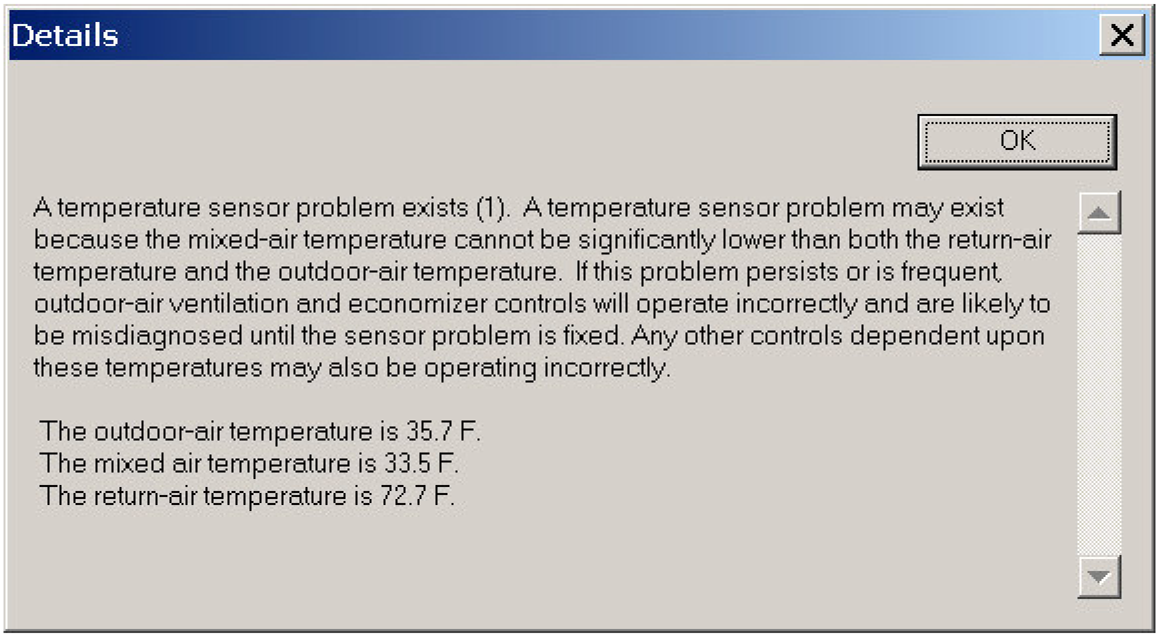


Figure 62 – Details Dialogue for AHU-3 on February 15, 2001, at 3:00 p.m. Indicating that a Temperature Sensor Problem has Occurred

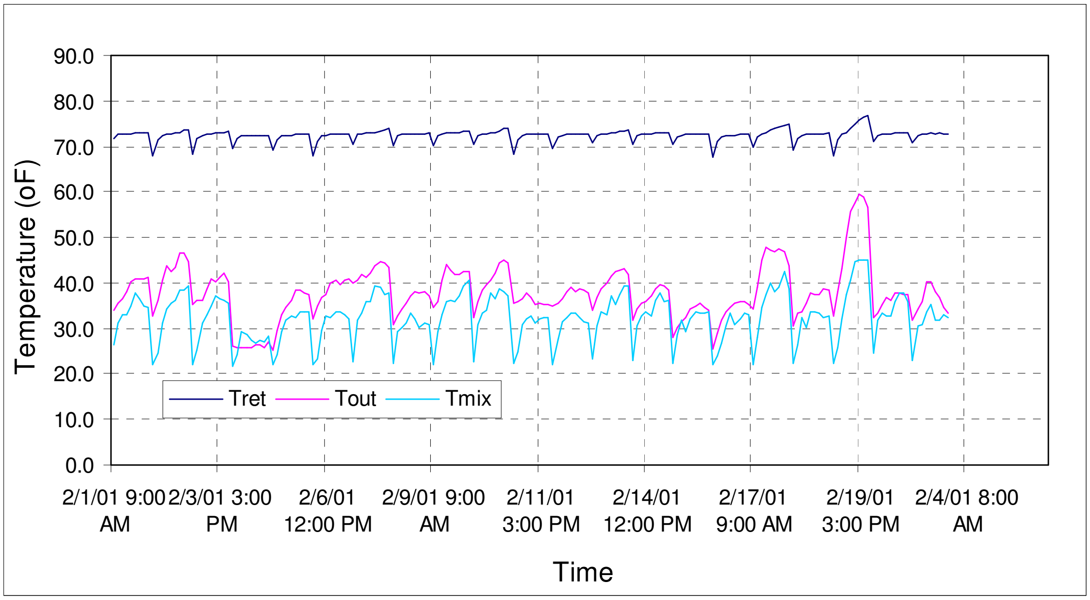


Figure 63 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z3-HS-F4

Table 5 – Frequency of the Problems for AHU-3 when the Building is Occupied (data set Z3-HS-F4) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.657	176	93.1
Control Problem – Excess Energy		0	0.0
Excess Ventilation		0	0.0
Inadequate Ventilation		0	0.0
Low Economizer Flow		0	0.0
OK but incomplete		0	0.0
Operation OK	0.657	13	6.9
Total		189	100

6.5.7 Data Set Z1-SS-F6

The data set Z1-SS-F6 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on swing-season weather data. Figure 64 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. More than half the cells are white (indicating normal operation) and the rest are yellow, blue and red. Although the fault associated with each of the three colors is different, browsing through the colored cells indicates a single common cause shared by many of them, a temperature sensor problem (Figure 65).

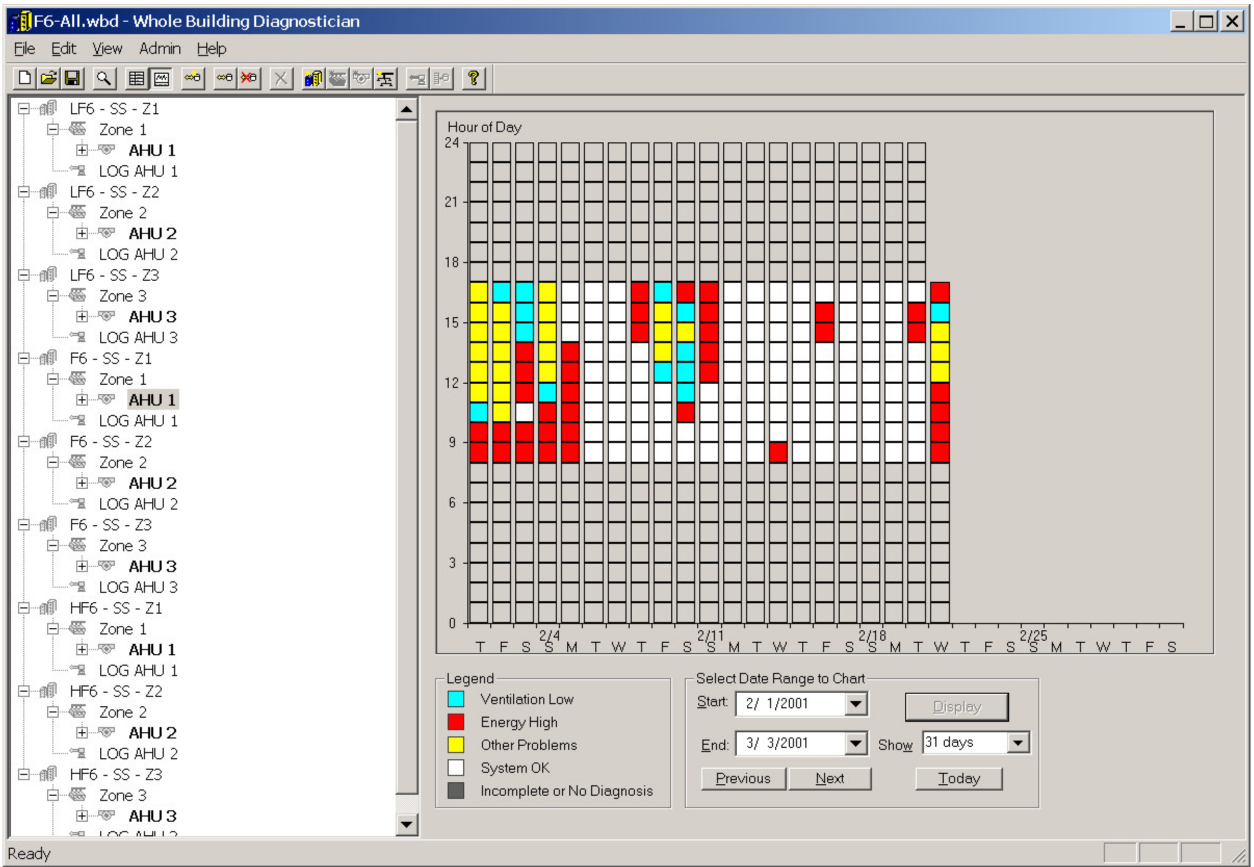


Figure 64 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-SS-F6 for Swing Season Weather with Normal OAE Sensitivity

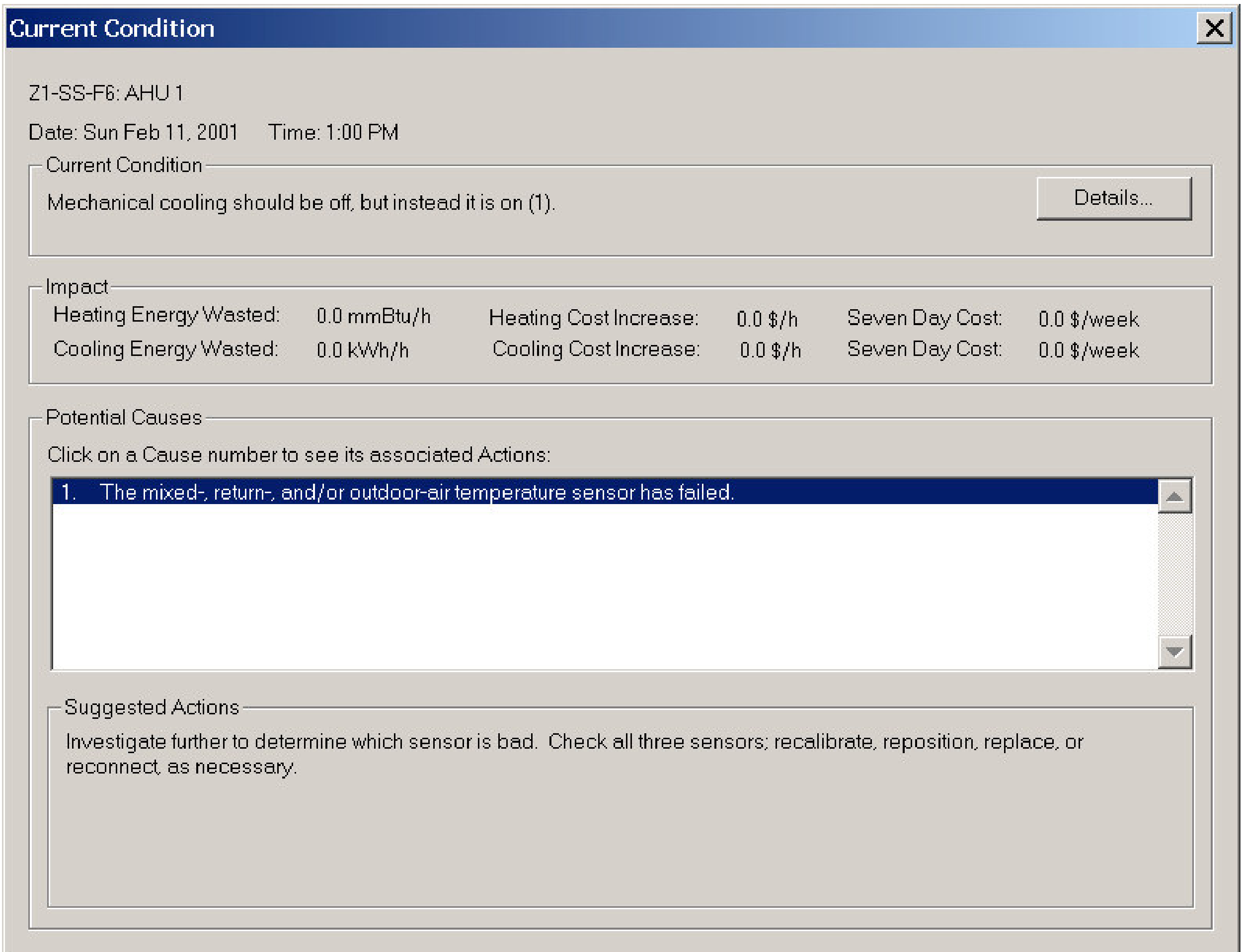


Figure 65 – Current Conditions Dialogue for AHU-1 on February 11, 2001, at 1:00 p.m. for Blind Test Data Set Z1-SS-F6

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and fraction of total occupied hours in each category are shown in Table 6. For the Z1-SS-F6 test, 60% of the time the OAE reported normal operation, 33% a control problem, and 7% inadequate ventilation.

Further manual analysis of the raw data indicates that the data set corresponded to a faulty outdoor-air temperature sensor that was reading a constant temperature over the 3 week period, as shown in Figure 66.

For Z1-SS-F6, the OAE diagnostician reported a temperature sensor problem.

Table 6 – Frequency of the Problems for AHU-1 when the Building is Occupied (Z1-SS-F6) with Normal Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.869	24	12.7
Control Problem – Excess Energy	0.500	38	20.1
Excess Ventilation		0	0.0
Inadequate Ventilation	0.869	13	6.9
Low Economizer Flow		0	0.0
OK but incomplete		0	0.0
Operation OK	0.744	114	60.3
Total		189	100

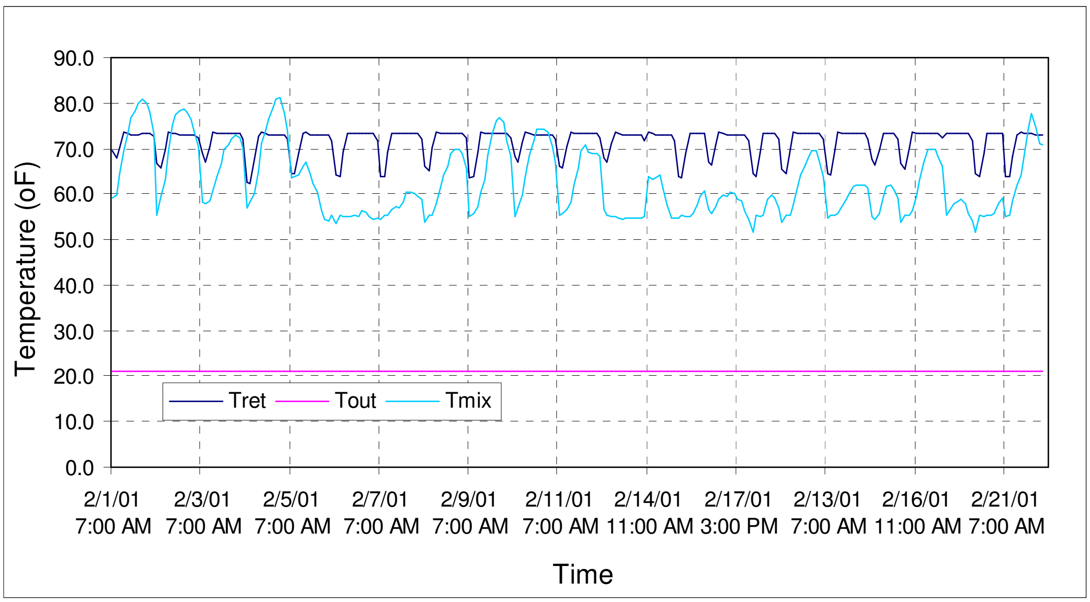


Figure 66 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z1-SS-F6

6.5.8 Data Set Z2-SS-F6

The data set Z2-SS-F6 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on swing-season weather data. Figure 67 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few yellow, red, blue, and gray cells, most cells are white. Browsing through the colored cells revealed no potential causes for most cells (Figure 68). Increasing the sensitivity of detection did not change the number of colored cells, but a single cause was reported in almost all cases, as shown in Figure 69.

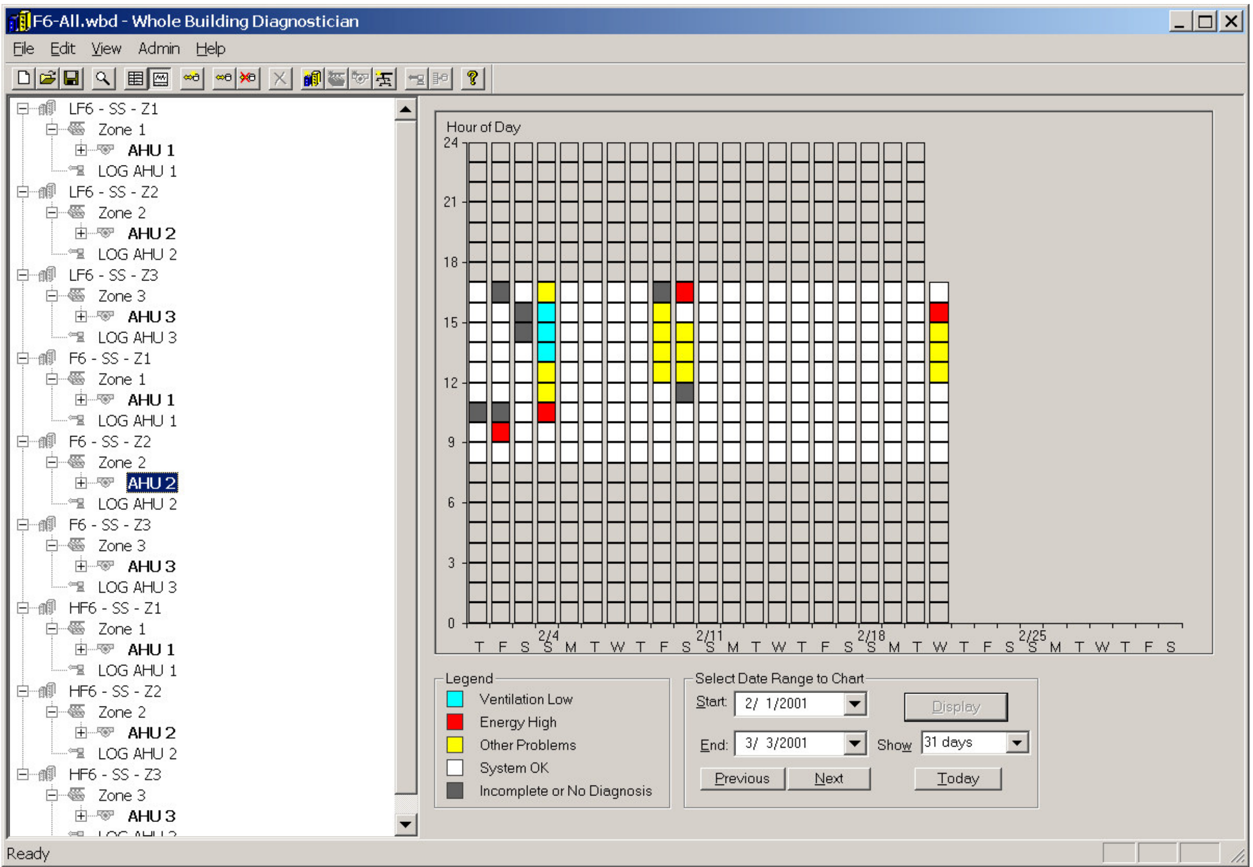


Figure 67 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-SS-F6 for Swing Season Weather with Normal OAE Sensitivity

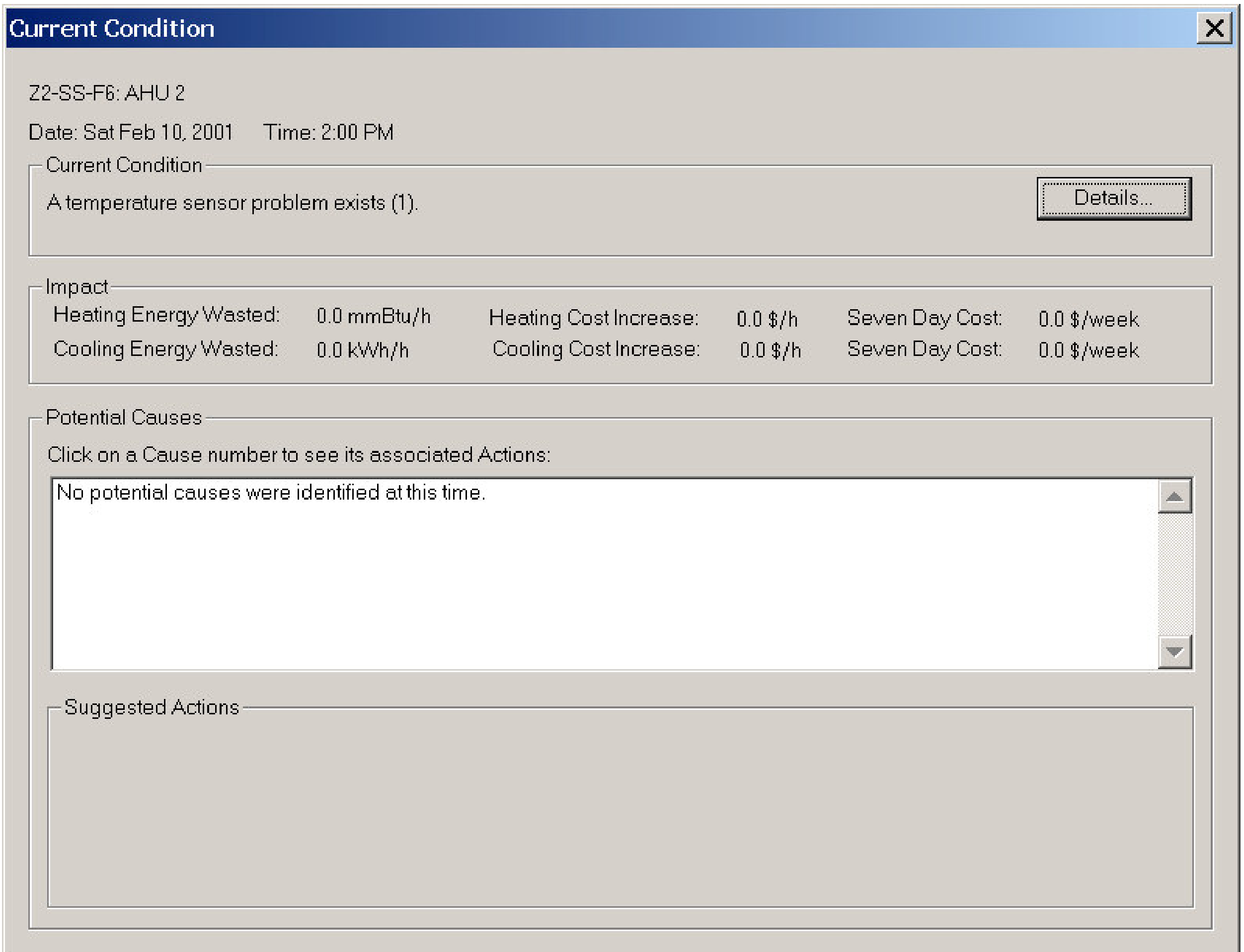


Figure 68 – Current Conditions Dialogue for AHU-2 on February 10, 2001, at 2:00 p.m. for Blind Test Data Set Z2-SS-F6 with the Normal OAE Sensitivity Setting

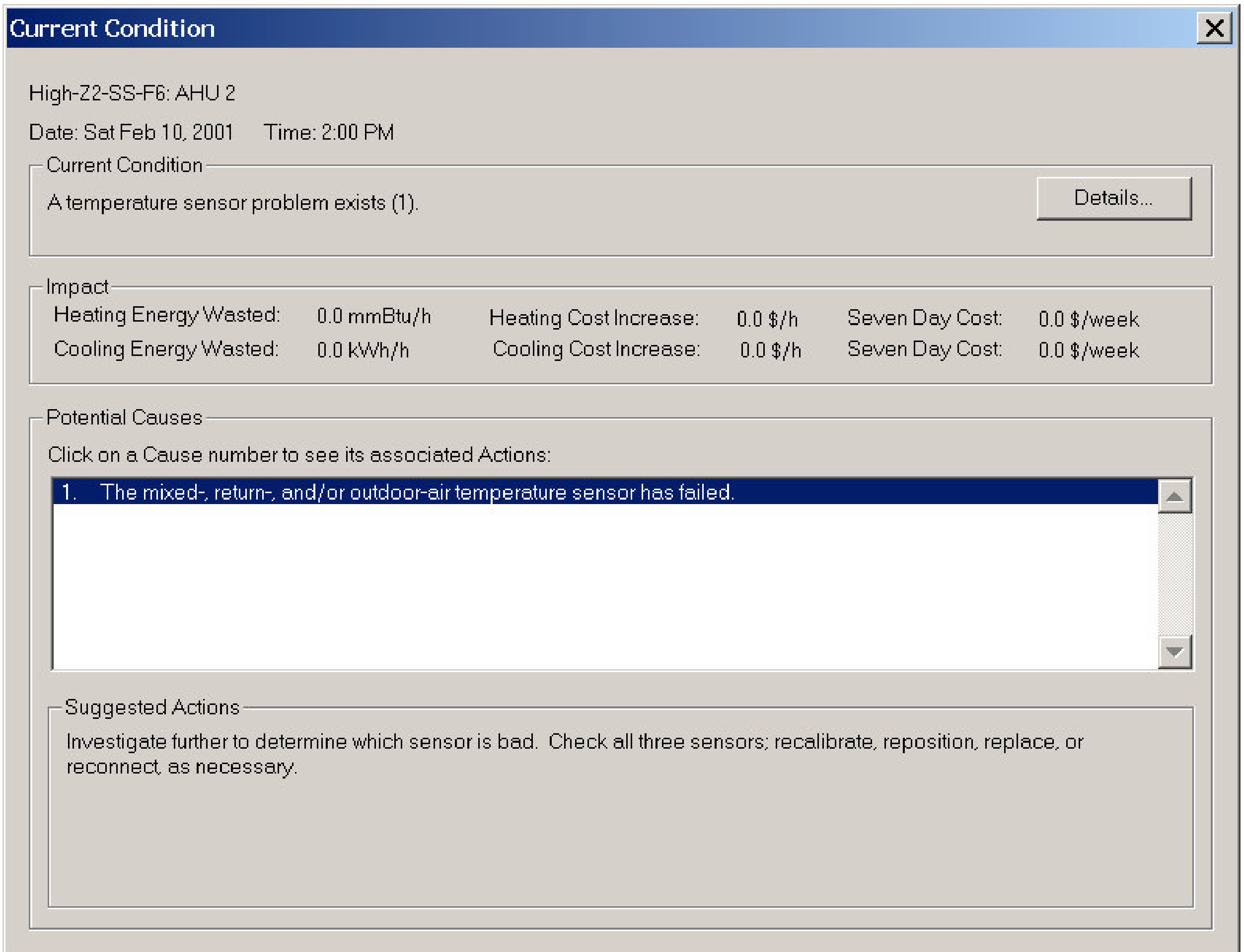


Figure 69 – Current Conditions Dialogue for AHU-2 on February 10, 2001, at 2:00 p.m. for Blind Test Data Set Z2-SS-F6 with the High OAE Sensitivity Setting

The frequency of problems reported by the OAE in each major category, the corresponding reliability score and fraction of total occupied hours in each category are shown in Table 7. For data set Z2-SS-F6, 86% of the time the OAE reported normal operation, 7% control problem, 2% inadequate ventilation, 2% low economizer flow, and 4% incomplete diagnosis.

Table 7 – Frequency of the Problems for AHU-2 when the Building is Occupied (Z2-SS-F6) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.657	13	6.9
Control Problem – Excess Energy		0	0.0
Excess Ventilation		0	0.0
Inadequate Ventilation	0.657	3	1.6
Low Economizer Flow	0.802	4	2.1
OK but incomplete	0.775	7	3.7
Operation OK	0.542	162	85.7
Total		189	100

A closer look at raw data indicates a drift in the return-air temperature sensor. The drift could not be detected on a consistent basis because of unfavorable outdoor-air conditions. When the conditions were favorable (conditions not favorable for economizing, i.e., when outdoor-air temperature > return-air temperature) for the fault to manifest, for example, on February 4, 9, and 10, the OAE detected the fault and reported a temperature sensor problem. Because the outdoor-air temperature for most times in this data set was lower than the return-air temperature, it did not affect the AHU operation. If the fault had continued into the summer season, it would have manifested more often because the outdoor air would have been warmer than the return air (conditions not favorable of economizing). Under those conditions, the measured mixed-air temperature should be between the measured outdoor- and return-air temperatures. If the measured mixed-air temperature were not in this range, a fault would be detected by the OAE. For more detailed explanation refer to section 6.5.3.

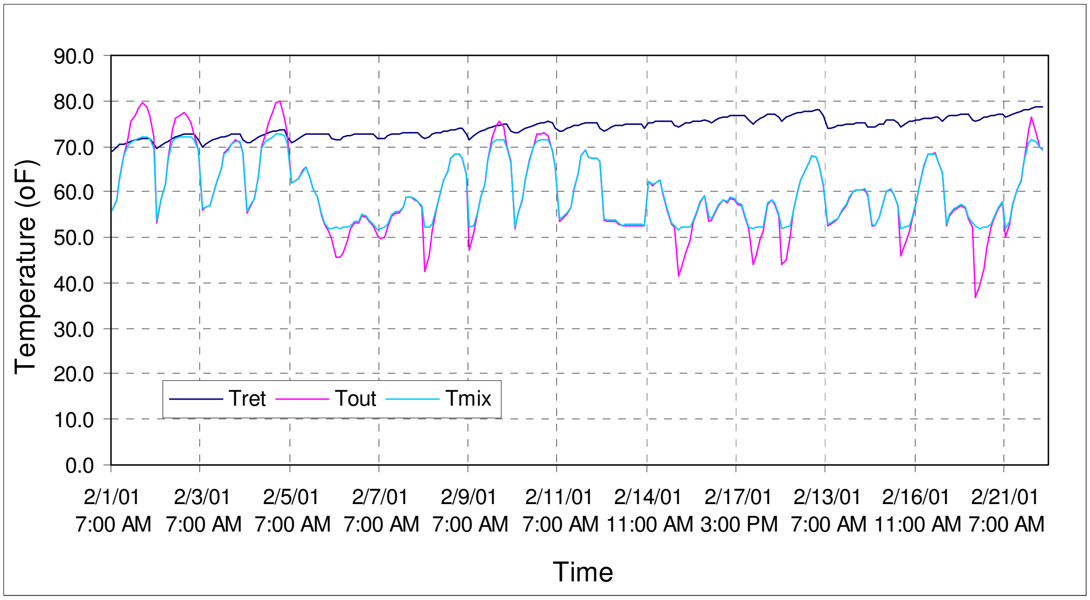


Figure 70 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z2-SS-F6

For Z2-SS-F6, the OAE diagnostician reported a temperature sensor problem.

6.5.9 Data Set Z3-SS-F6

The data set Z3-SS-F6 has three weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on swing-season weather data. Figure 71 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most of the cells are red, indicating energy waste. Browsing through the red cells reveals that the common problem reported is that the economizer should be operating fully open but it is only partial open (Figure 72). There are five to six potential causes reported for most cells, as shown in Figure 72. With the exception of potential causes 1 and 4, the other three causes are related to configuration/setup of the diagnostician. Therefore, the fault is attributable to the outdoor-damper system not fully opening when conditions are favorable for economizing either because the damper is stuck or the economizer controls are not properly functioning.

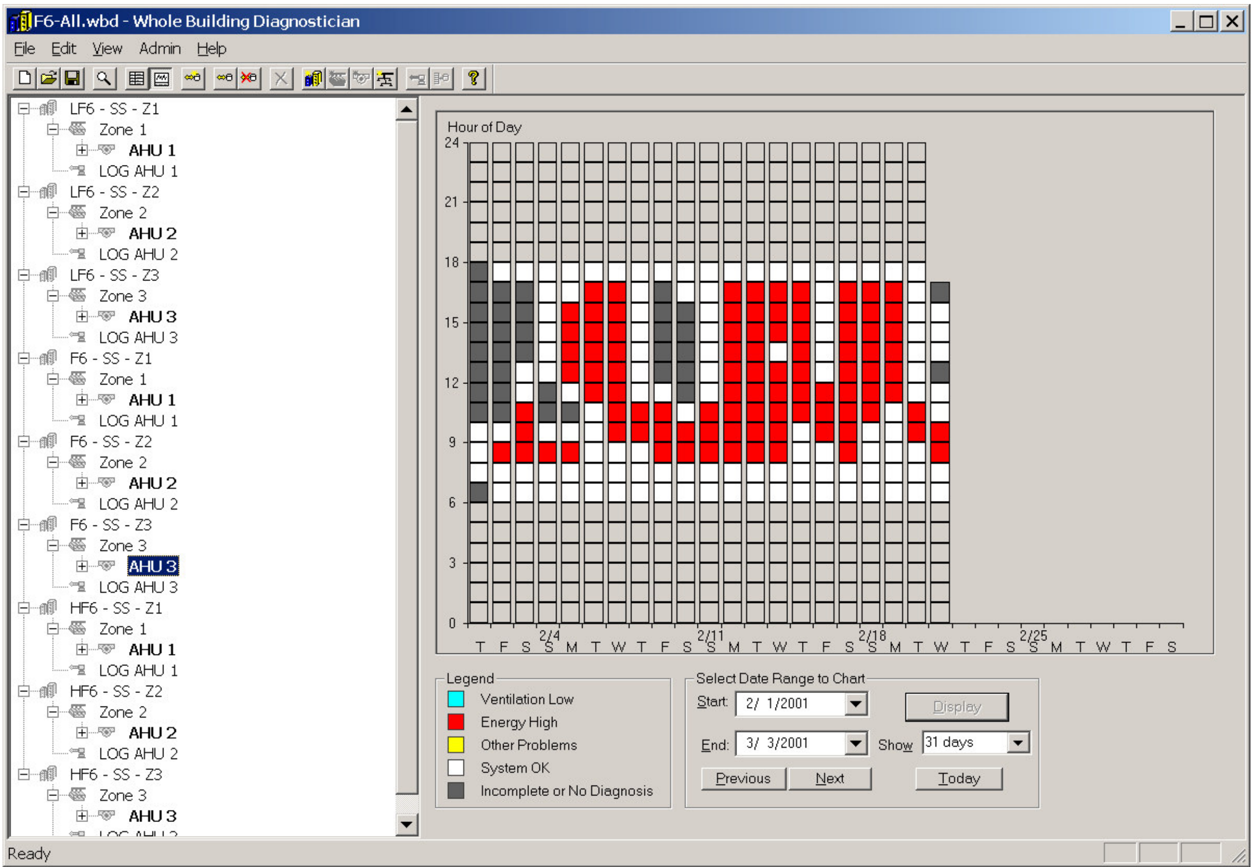


Figure 71 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F6 for Swing-Season Weather with Normal OAE Sensitivity

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and fraction of total occupied hours in each category are shown in Table 8. For data set Z3-SS-F6, 50% of the time the OAE reported low economizer flow, 18% incomplete diagnosis and 32% normal operation.

For Z3-SS-F6, the OAE diagnostician reported low economizer flow caused by the outdoor-air damper being stuck or improper economizer control.

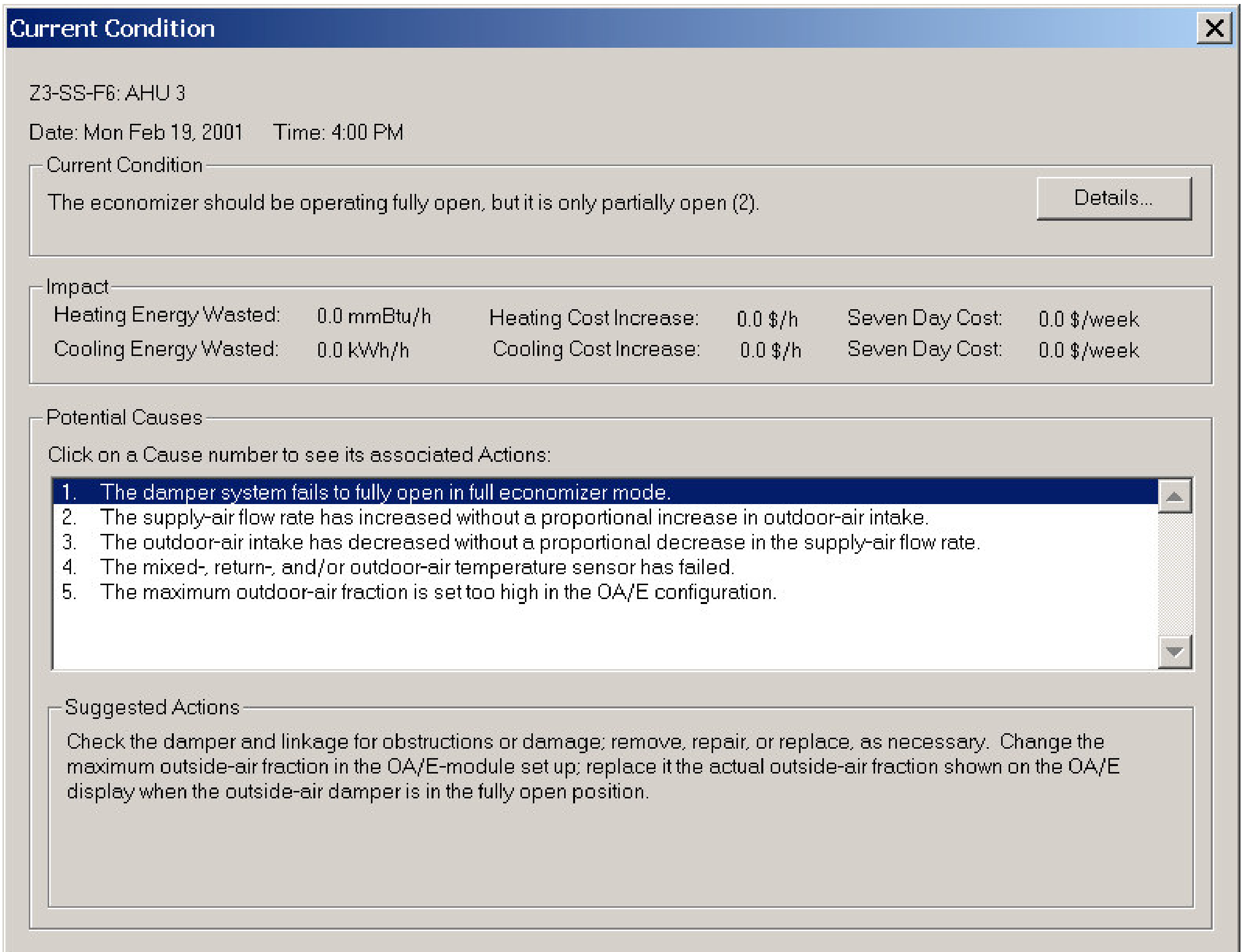


Figure 72 – Current Conditions Dialogue for AHU-3 on February 19, 2001, at 4:00 p.m. for Blind Test Data Set Z3-SS-F6

Table 8 – Frequency of the Problems for AHU-3 when the Building is Occupied (data set Z3-SS-F6) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem		0	0.0
Control Problem – Excess Energy		0	0.0
Excess Ventilation		0	0.0
Inadequate Ventilation		0	0.0
Low Economizer Flow	0.553	96	50.8
OK but incomplete	0.621	33	17.5
Operation OK	0.583	60	31.7
Total		189	100.0

6.5.10 Data Set Z1-SS-F8

The data set Z1-SS-F8 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on swing-season weather data. Figure 73 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most of the cells are colored (yellow, red and blue). When a significant number of cells are yellow, it generally indicates a faulty temperature sensor. Browsing through the yellow cells confirms that the problem is a faulty temperature sensor (Figure 74).

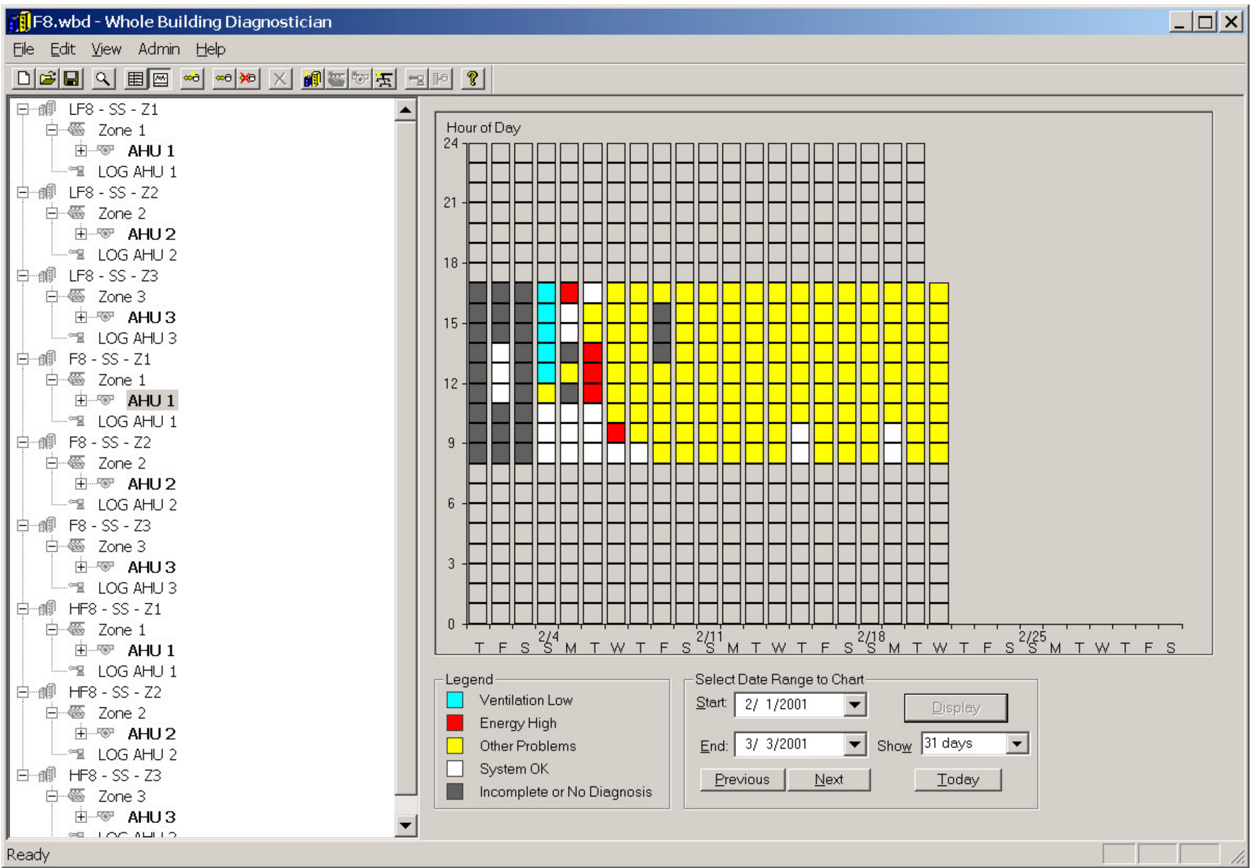


Figure 73 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-SS-F8 for Swing-Season Weather with Normal OAE Sensitivity

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and fraction of total occupied hours in each category are shown in Table 9. For data set Z1-SS-F8, over 68% of the time the OAE reported control problems (other problems), 2% inadequate ventilation, 15% incomplete diagnosis, and 11% fault-free operation.

A closer look at the raw data indicates that no fault with the return-air temperature sensor exists because it is in the expected range, so either the outdoor- or the mixed-air temperature sensor is faulty (Figure 75).

For Z1-SS-F8, the OAE diagnostician reported a temperature sensor problem.

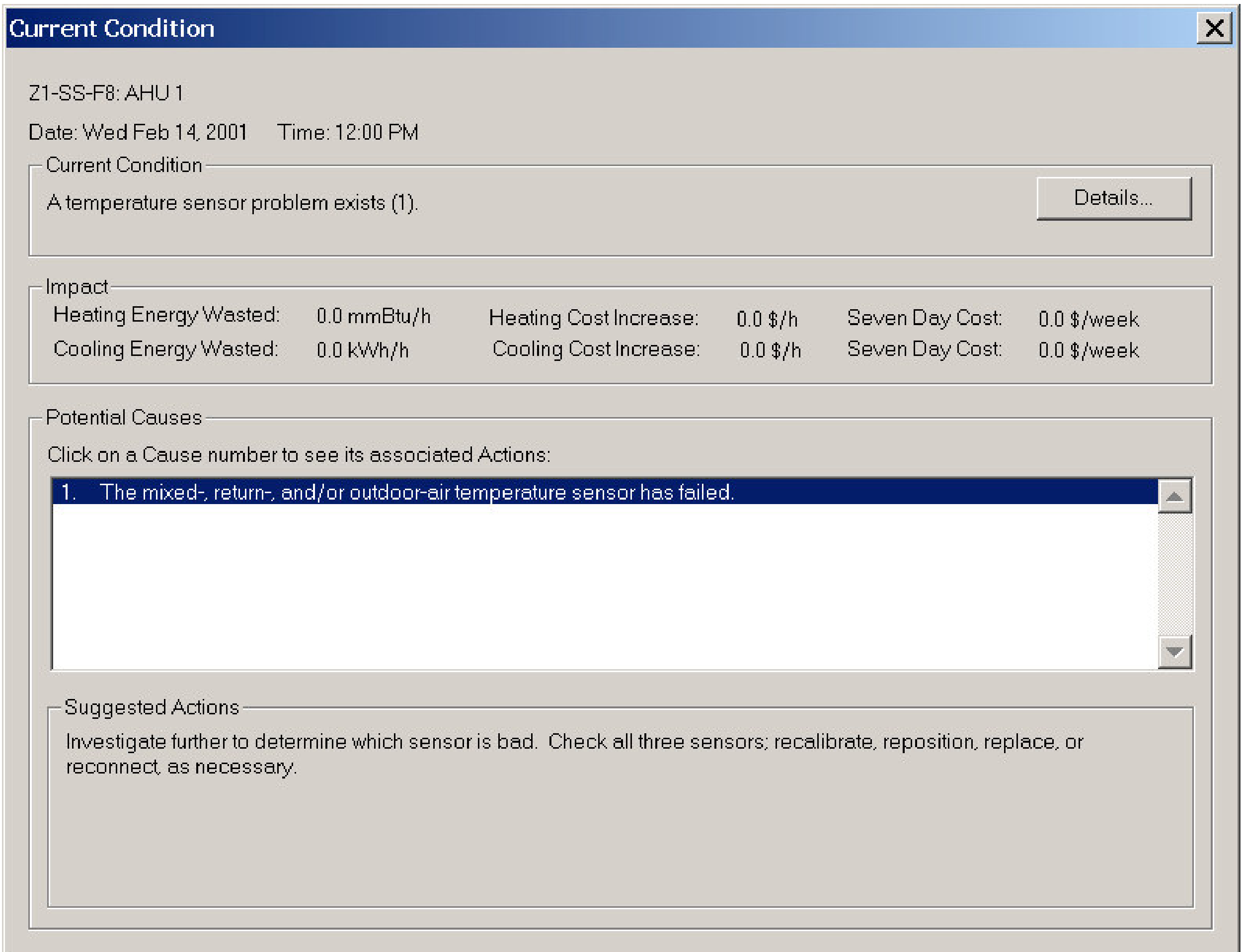


Figure 74 – Current Conditions Dialogue for AHU-1 on February 14, 2001, at 12:00 p.m. for Blind Test Data Set Z1-SS-F8

Table 9 – Frequency of the Problems for AHU-3 when the Building is Occupied (data set Z1-SS-F8) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.889	129	68.3
Control Problem – Excess Energy	0.500	1	0.5
Excess Ventilation		0	0.0
Inadequate Ventilation	0.667	5	2.6
Low Economizer Flow	0.954	4	2.1
OK but incomplete	0.655	29	15.3
Operation OK	0.642	21	11.1
Total		189	100.0

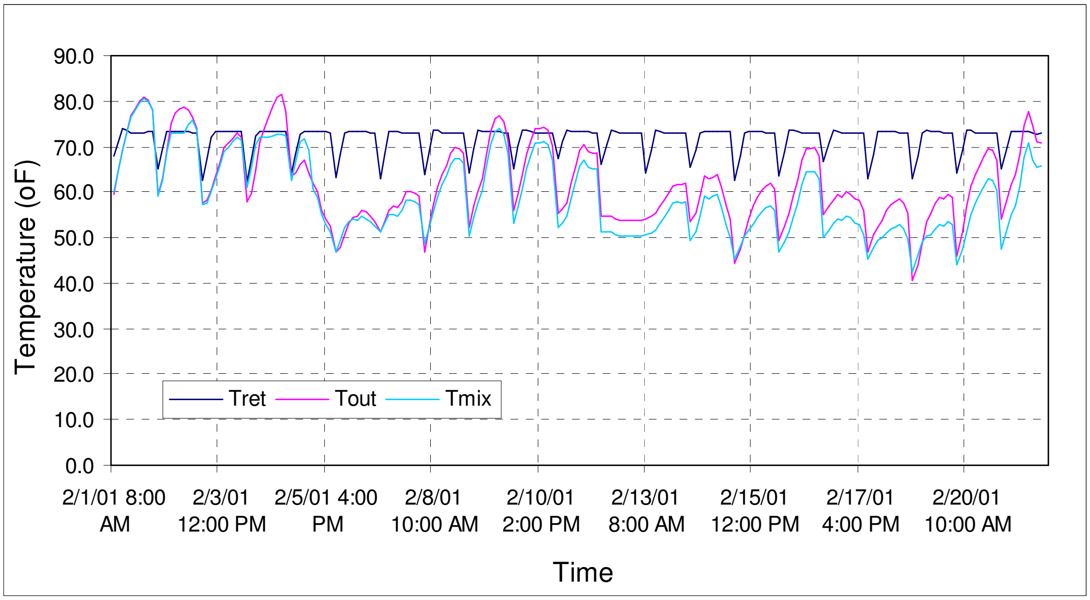


Figure 75 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z1-SS-F8

6.5.11 Data Set Z2-SS-F8

The data set Z2-SS-F8 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on swing-season weather data. Figure 76 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and red cells, most of the cells are white, indicating normal operation. Increasing the sensitivity of detection introduced a number of blue cells, as shown in Figure 77. Browsing a number of these blue cells indicates that the fault is attributable to inadequate ventilation during occupied hours while not economizing; however, a number of different potential causes are listed for the fault, as shown in Figure 78. The most likely causes of the fault are that the outdoor-air damper is stuck in a fully-closed position and that a temperature sensor has failed.

For Z2-SS-F8, the OAE diagnostician reported that either the outdoor-air damper is stuck in a fully-closed position or a temperature sensor has failed when set at high sensitivity. At normal sensitivity, no problem was detected.

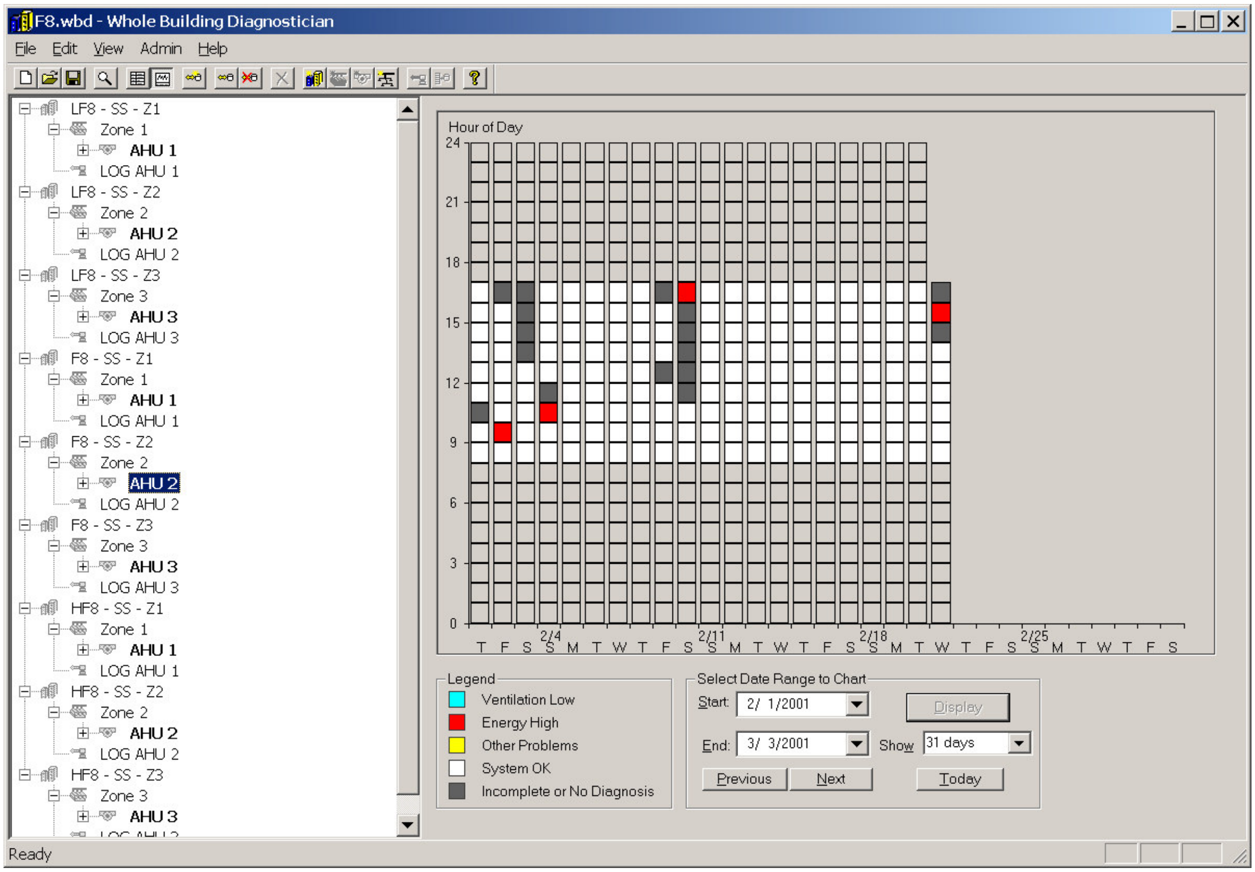


Figure 76 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z2-SS-F8 for Swing-Season Weather with Normal OAE Sensitivity

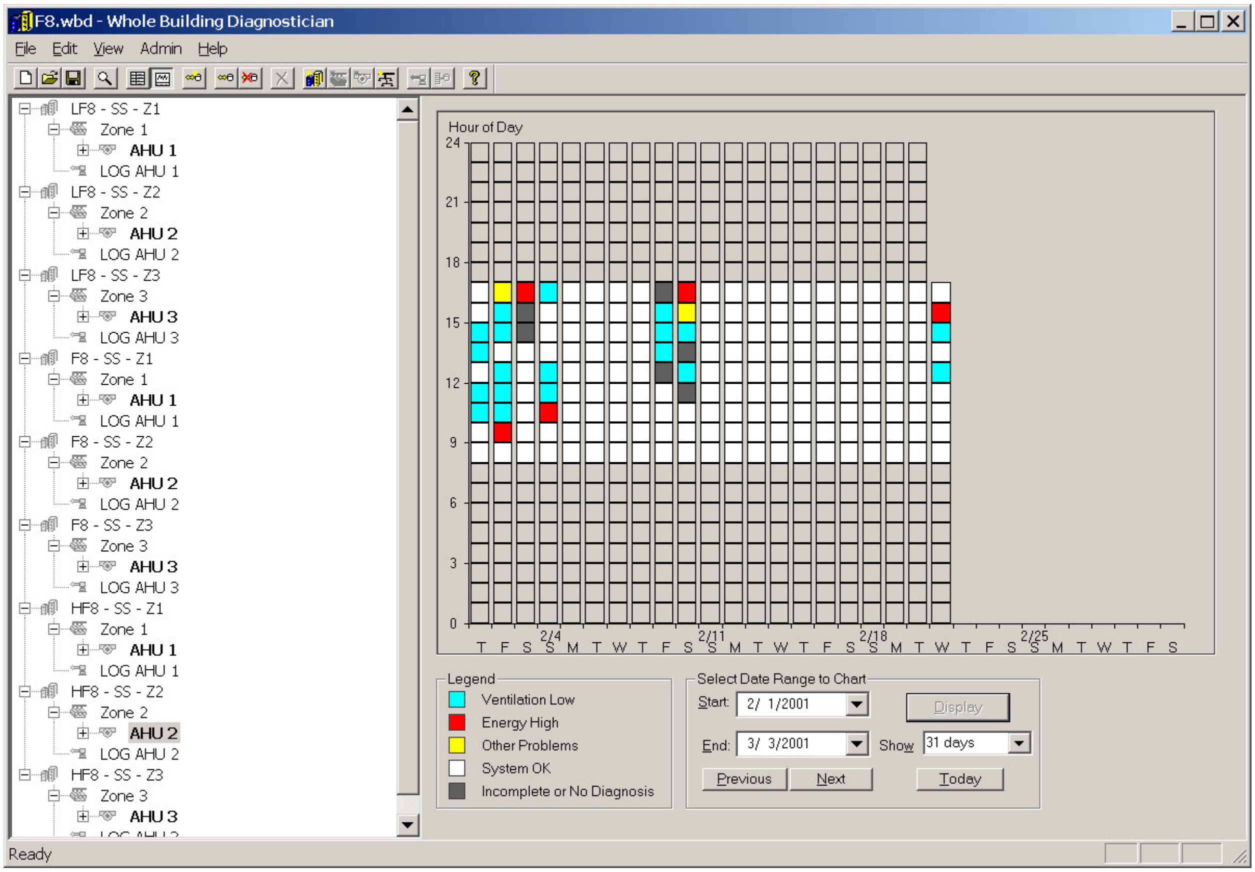


Figure 77 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-SS-F8 for Swing-Season Weather with High OAE Sensitivity

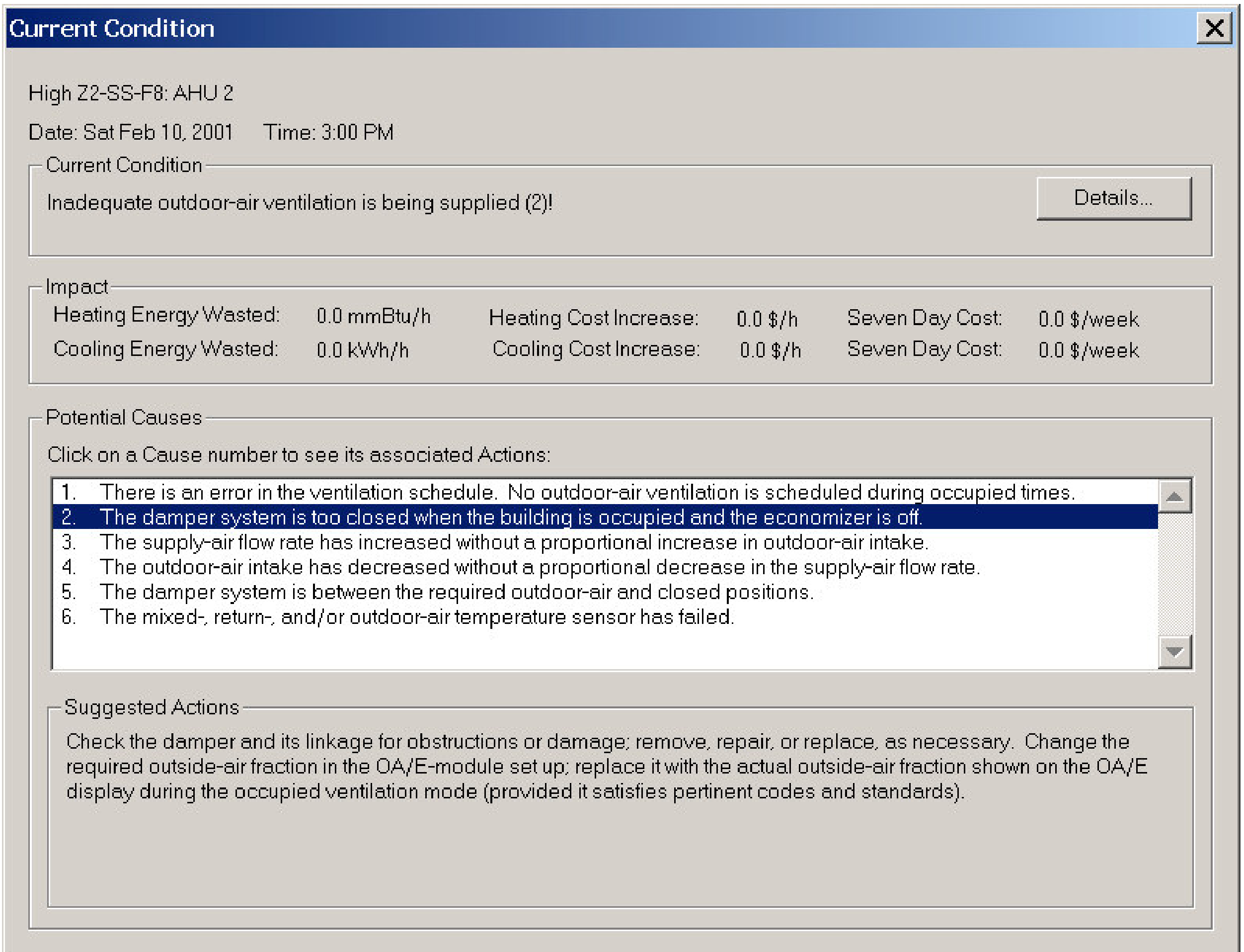


Figure 78 – Current Conditions Dialogue for AHU-2 on February 10th, 2001, at 3:00 P.M. for Blind Test Data Set Z2-SS-F8

6.5.12 Data Set Z3-SS-F8

The data set Z3-SS-F8 has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on swing-season weather data. Figure 79 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most of the cells are red, indicating energy waste. Browsing through the red cells reveals a common problem, the economizer should be operating fully open, but it is only partially open (Figure 80). The list of potential causes for the fault include two configuration issues, two related to air flow, one in which the outdoor-air damper is stuck between fully open and its minimum position, and one in which the outdoor-air damper is not fully open.

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total occupied hours in each category are shown in Table 10. For the Z3-SS-F8 data set, almost 50% of the time is reported by the OAE as having low economizer flow, 18% with incomplete diagnosis, and 32% with normal operation.

For Z3-SS-F8, the OAE diagnostician reports a damper stuck between the minimum and fully open positions.

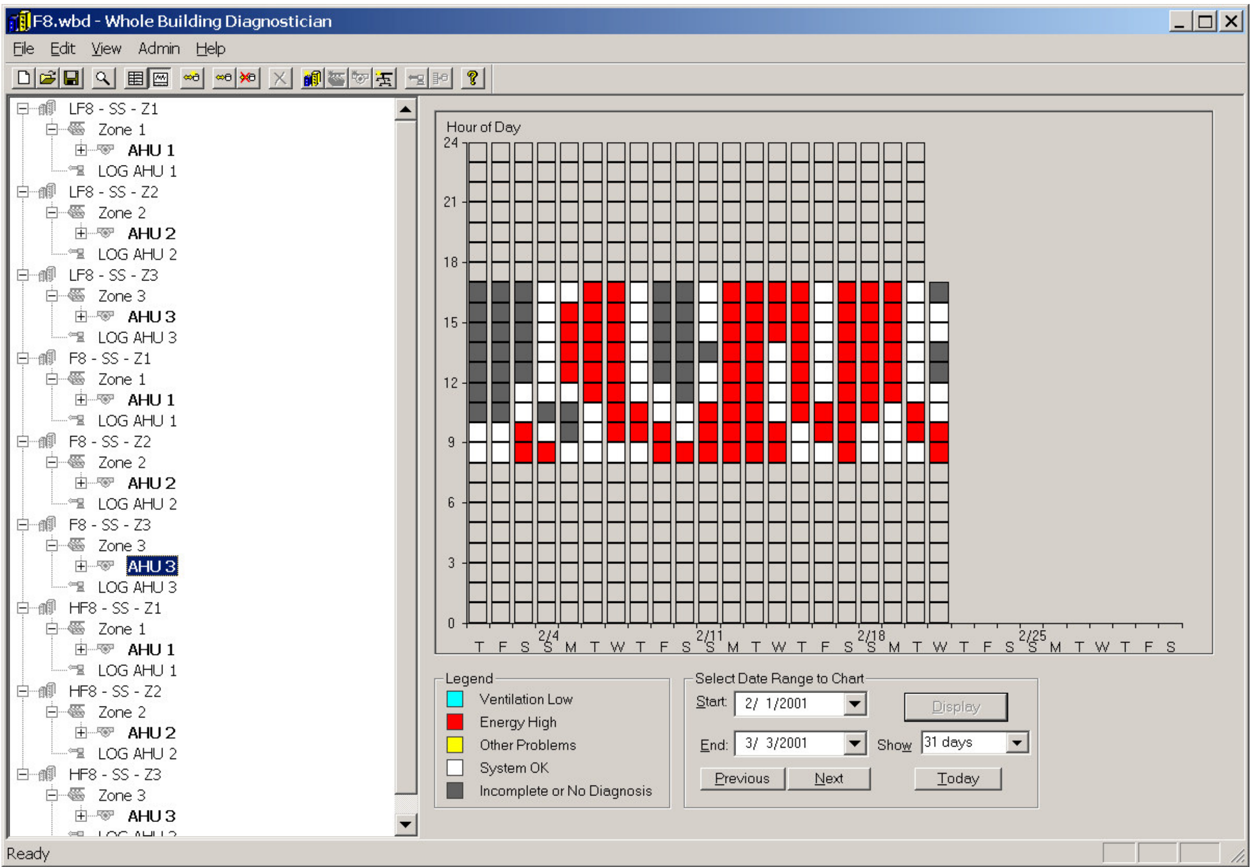


Figure 79 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F8 for Swing-Season Weather with Normal OAE Sensitivity

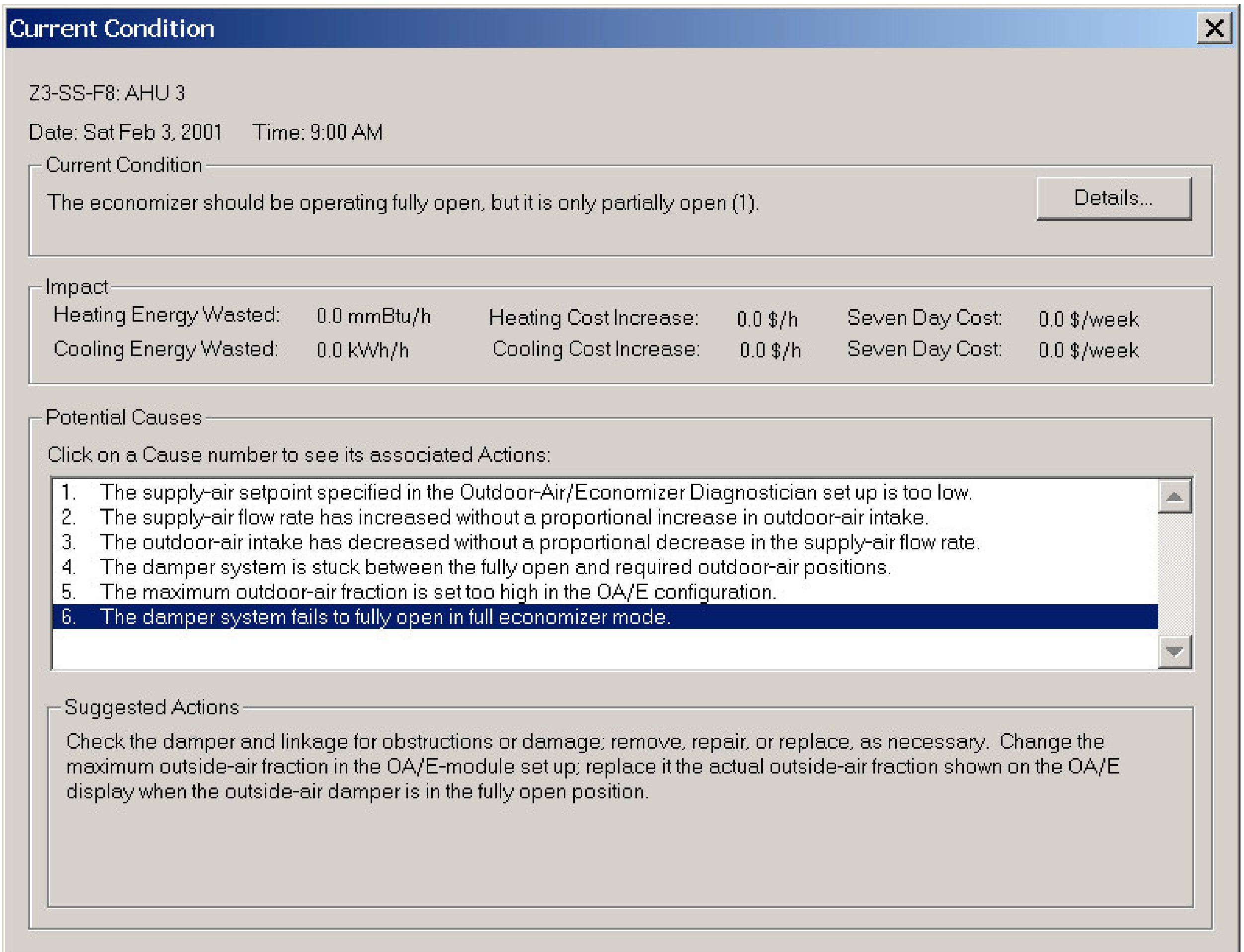


Figure 80 – Current Conditions Dialogue for AHU-3 on February 3, 2001, at 9:00 a.m. for Blind Test Data Set Z3-SS-F8

Table 10 – Frequency of Problems for AHU-3 when the Building is Occupied (data set Z3-SS-F8) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem		0	0.0
Control Problem – Excess Energy		0	0.0
Excess Ventilation		0	0.0
Inadequate Ventilation		0	0.0
Low Economizer Flow	0.550	97	48.7
OK but incomplete	0.618	37	18.6
Operation OK	0.593	65	32.7
Total		199	100.0

6.5.13 Data Set Z1-CS-F9

The data set Z1-CS-F9 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on cooling-season weather data. Figure 81 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray cells, most cells are white, indicating proper AHU operation. However, increasing the sensitivity of detection introduced many blue cells, as shown in Figure 82. Browsing through the blue cells indicates inadequate ventilation during occupied hours. The list of potential causes is long, as shown in Figure 83; however, most of them are related (inadequate ventilation).

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total unoccupied hours in each category are shown in Table 11. For the Z1-CS-F9 data set, over 50% of the time, the OAE reported inadequate ventilation flow, and the rest of the time, it reported incomplete or normal operation.

For Z1-CS-F9, the OAE diagnostician reported normal operation using normal sensitivity setting; however, when the sensitivity setting was increased, it reported an outdoor-air damper stuck between minimum and closed position, which represents faulty operations.

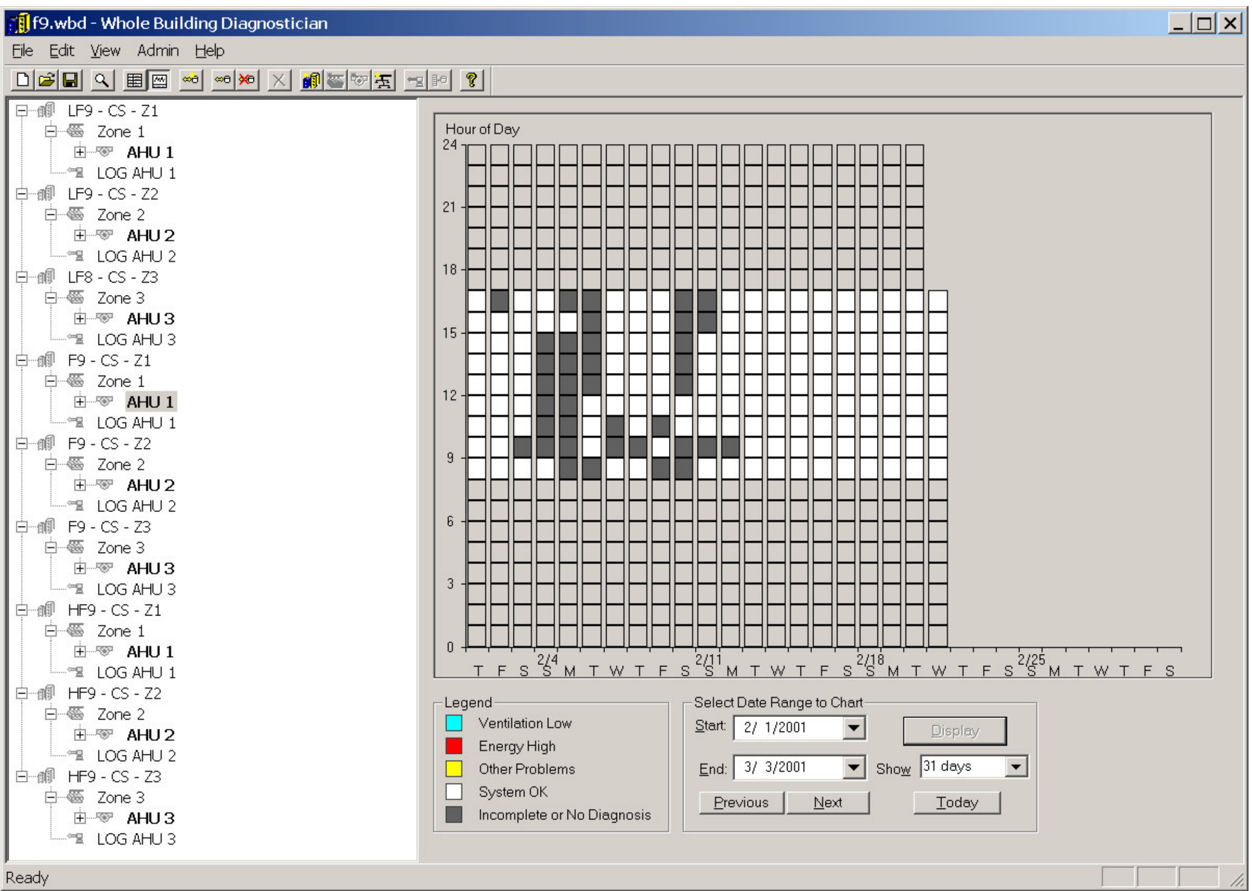


Figure 81 – WBD's Diagnostic Results View for AHU-1 with Blind Test Data Z1-CS-F9 from Cooling Season with Normal Sensitivity

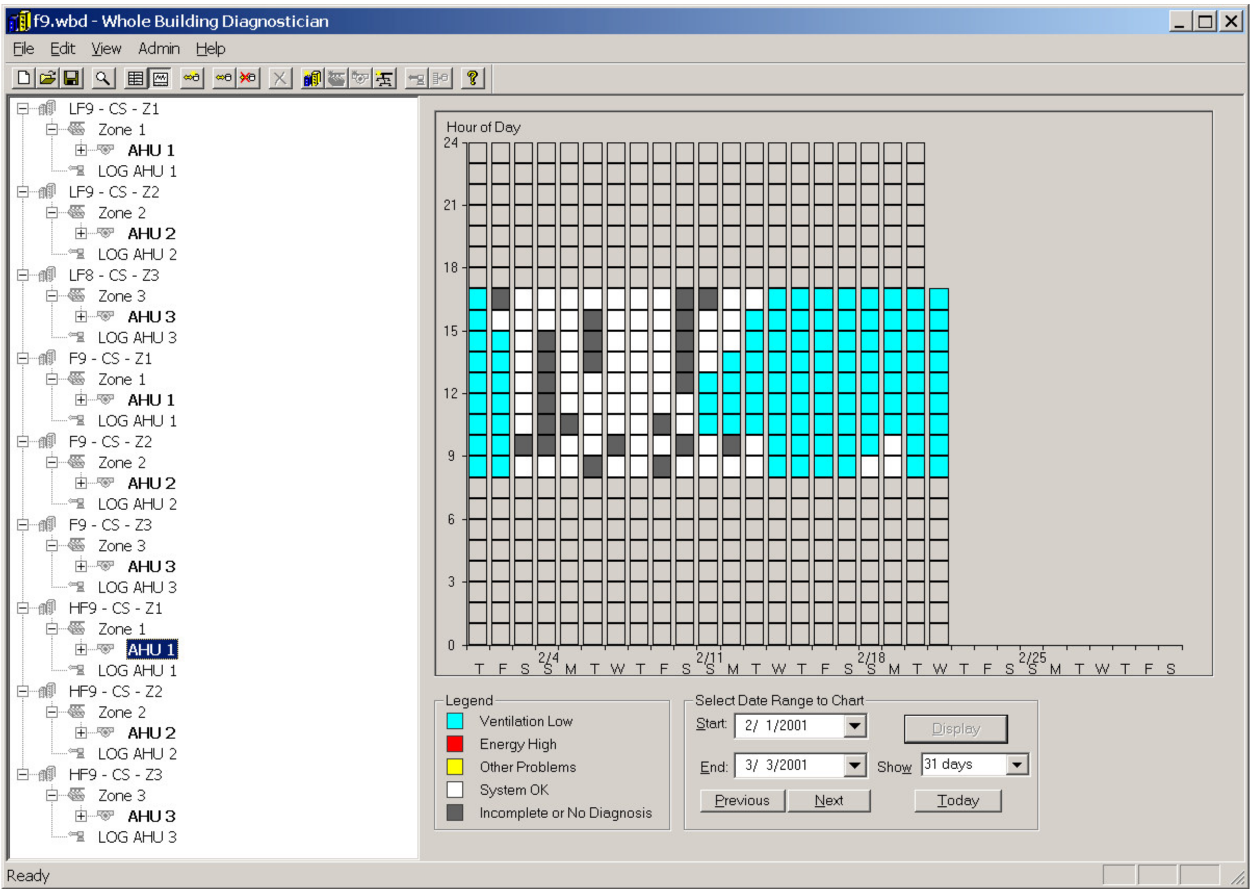


Figure 82 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-CS-F9 for Cooling Season Weather with High OAE Sensitivity

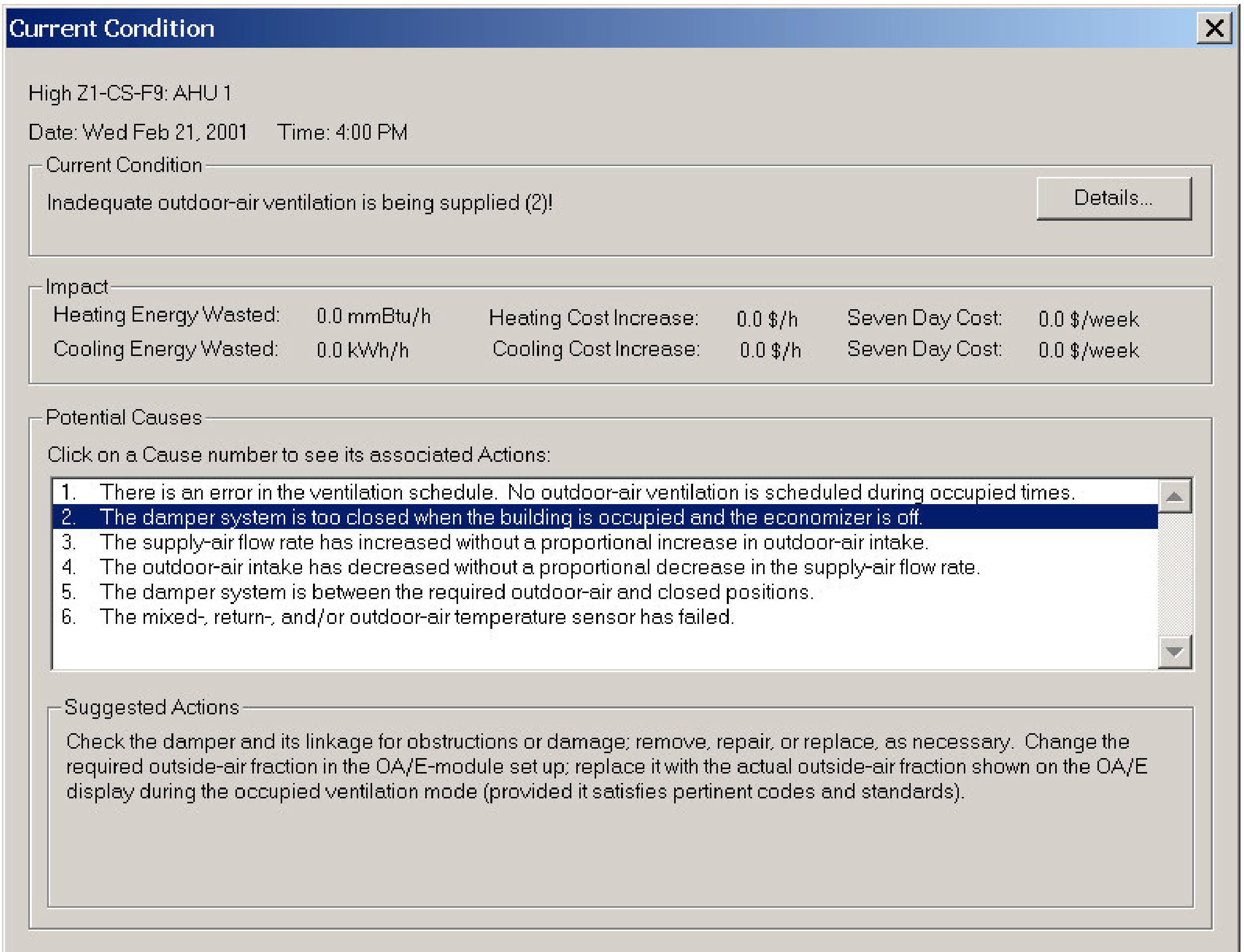


Figure 83 – Current Conditions Dialogue for AHU-1 on February 21, 2001, at 4:00 p.m. for Blind Test Data Set Z1-CS-F9

Table 11 – Frequency of Problems for AHU-1 when the Building is Occupied (data set Z1-CS-F9) with High OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem		0	0.0
Control Problem – Excess Energy		0	0.0
Excess Ventilation		0	0.0
Inadequate Ventilation	0.923	98	51.9
Low Economizer Flow		0	0.0
OK but incomplete	0.826	24	12.7
Operation OK	0.907	67	35.4
Total		189	100.0

6.5.14 Data Set Z2-CS-F9

The data set Z2-CS-F9 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on cooling-season weather data. Figure 84 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most cells are red indicating an energy wasting problem. Browsing through many of the red cells reveals that the economizer is operating even when conditions are not favorable for economizing. The list of potential causes for the fault is long, as shown in Figure 85; however, many of these causes are related. The most probable cause of the fault is an economizer controller failure.

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total hours in each category are shown in Table 12. For the Z2-CS-F9 test, over 70% of the time, the OAE reported excess ventilation flow, and the rest of the time, it mostly reported incomplete or normal operation.

For Z2-CS-F9, the OAE diagnostician reported a controller failure or that the outdoor-air damper stuck in a fully-open position.

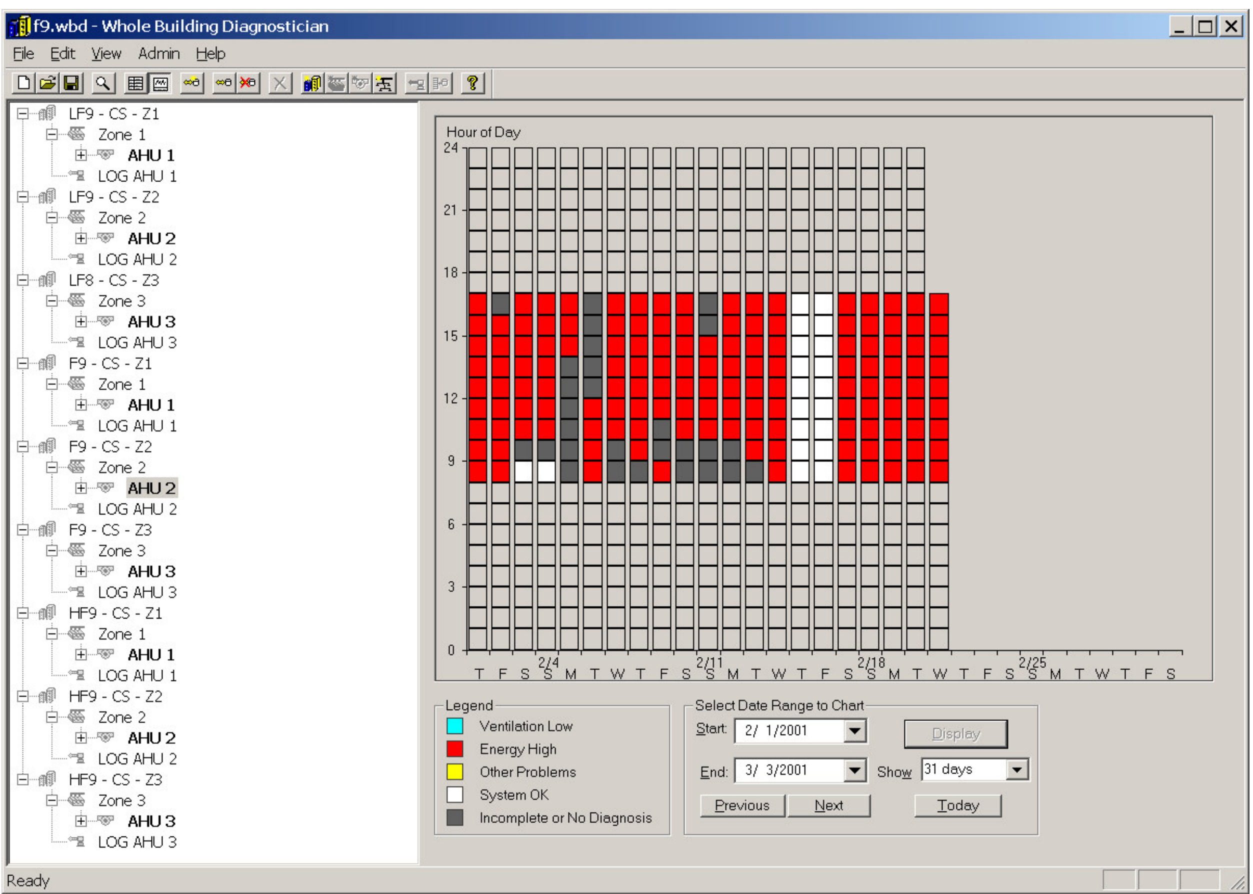


Figure 84 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-CS-F9 for Cooling Season Weather with Normal OAE Sensitivity

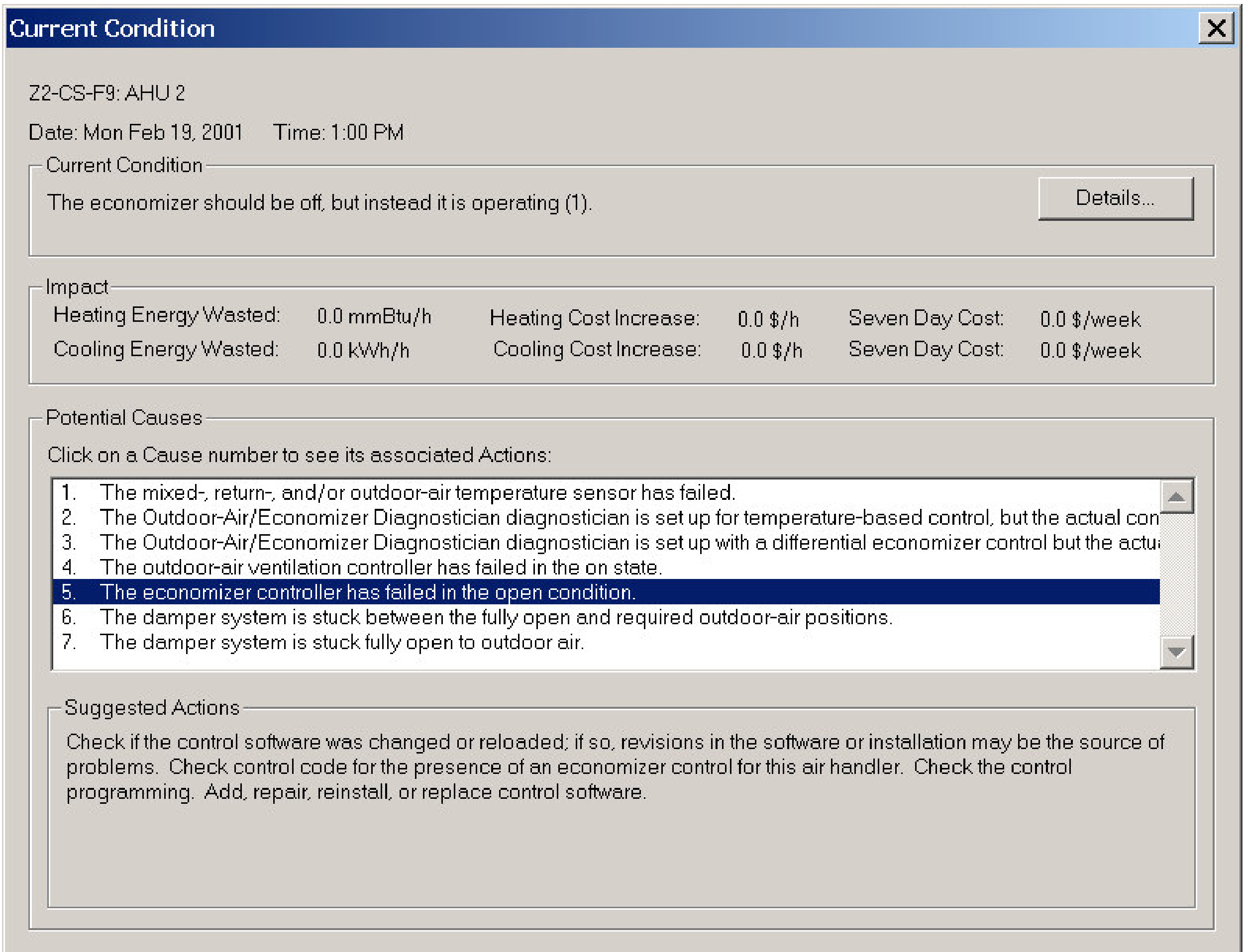


Figure 85 – Current Conditions Dialogue for AHU-2 on February 19, 2001, at 1:00 p.m. for Blind Test Data Set Z2-CS-F9

Table 12 – Frequency of Problems for AHU-2 when the Building is Occupied (data set Z2-CS-F9) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem		0	0.0
Control Problem – Excess Energy		0	0.0
Excess Ventilation	0.875	136	72.0
Inadequate Ventilation		0	0.0
Low Economizer Flow	0.657	5	2.6
OK but incomplete	0.653	28	14.8
Operation OK	0.656	20	10.6

Total		189	100.0

6.5.15 Data Set Z3-CS-F9

The data set Z3-CS-F9 has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on cooling-season weather data. Figure 86 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most cells are yellow. Browsing through many of the yellow cells reveals a common problem: a faulty temperature sensor. The list of potential causes for the fault has just one cause, as shown in Figure 87. However, as previously noted, the OAE diagnostician cannot distinguish which of the three sensors is faulty (outdoor-, mixed- or return-air temperature sensor).

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total hours in each category are shown in Table 13. For the Z3-CS-F9 test, over 55% of the time, the OAE reported a control problem (Other). The rest of the time, it reported incomplete diagnosis or normal operation. A closer look at the raw data indicates a drifting return-air temperature sensor (Figure 88), but the OAE could detect that there was a temperature sensor problem. It could not isolate the problem to one sensor or indicate the specific nature of the problem as drifting.

For Z3-CS-F9, the OAE diagnostician reported a temperature sensor problem.

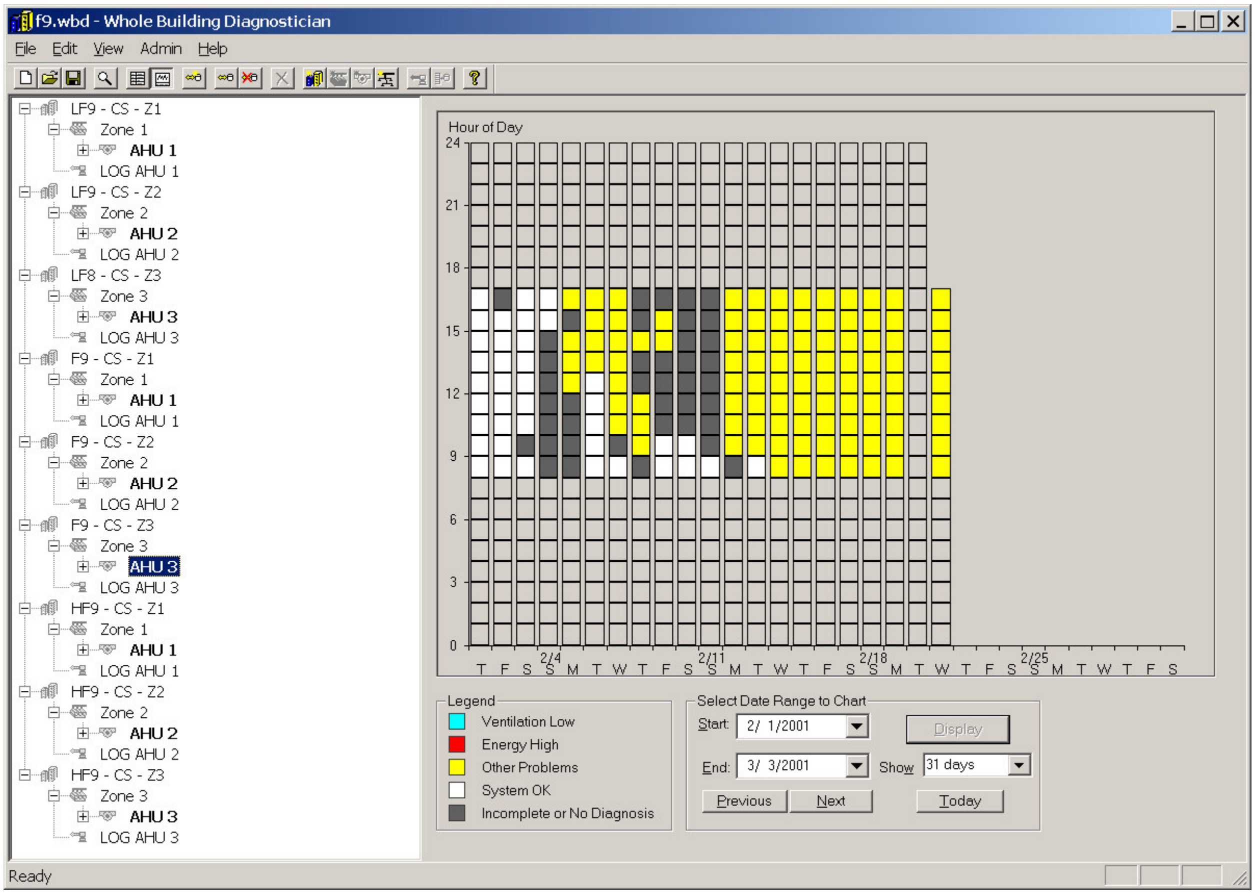


Figure 86 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-CS-F9 for Cooling Season Weather with Normal OAE Sensitivity

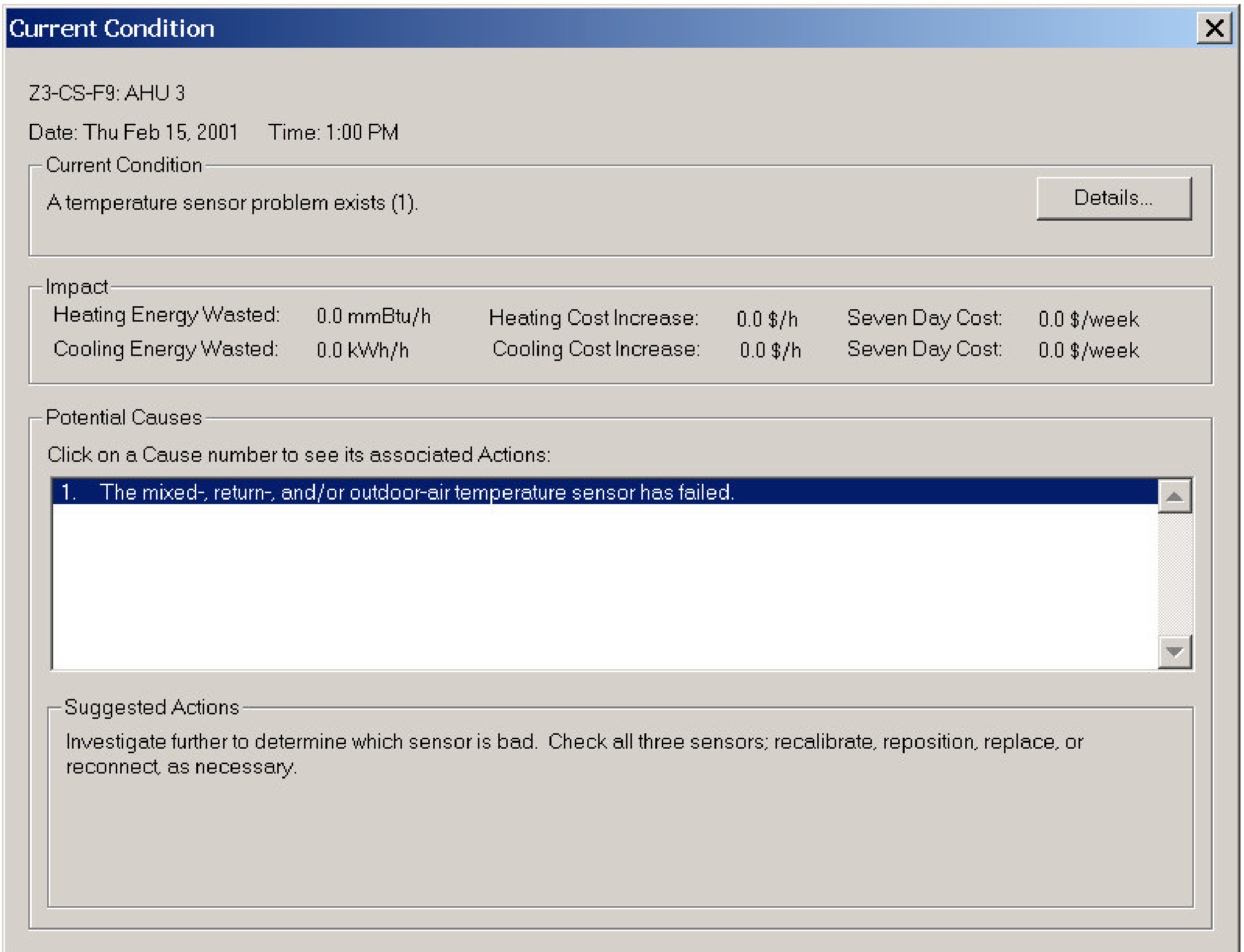


Figure 87 – Current Conditions Dialogue for AHU-3 on February 15, 2001, at 1:00 p.m. for Blind Test Data Set Z3-CS-F9

Table 13 – The frequency of Problems for AHU-2 when the Building is Occupied (data set Z3-CS-F9) with Normal OAE Sensitivity

Category of Operational States	Reliability Score	Number of Occurrences	Fraction of Total Occupied Hours (%)
Control Problem	0.663	100	55.6
Control Problem – Excess Energy		0	0.0
Excess Ventilation		0	0.0
Inadequate Ventilation		0	0.0
Low Economizer Flow		0	0.0
OK but incomplete	0.635	41	22.8
Operation OK	0.655	39	21.7
Total		180	100

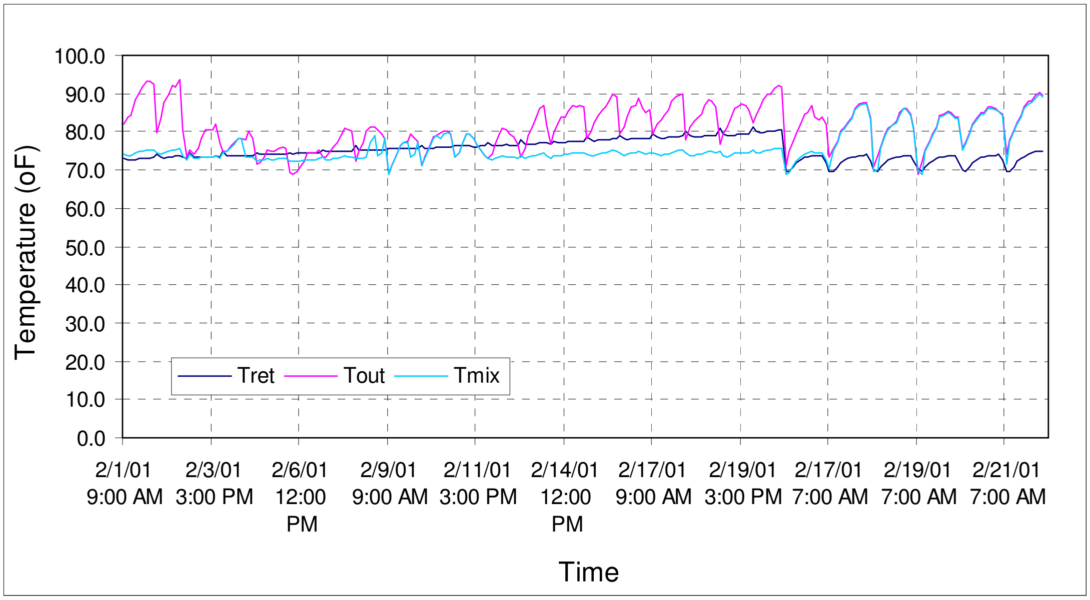


Figure 88 – Time Series Plot of the measured Return-, Outdoor-, and Mixed-air Temperatures for the Z3-CS-F9 Test

7 WBE Results

The results from automated processing of end-use energy consumption data sets with fault-free operation, operation with known faults for non-blind tests, and operation with faults for blind tests are presented in this section. All data sets have at least 12 months of data, although faulty operations generally span only a few months.

The Whole-Building Energy (WBE) diagnostician tracks end uses at the whole-building level, such as whole-building total electricity use, whole-building total thermal energy (cooling or heating) use, chiller or packaged unit energy consumption, or HVAC electricity consumption other than the chiller. Internally, the WBE modeling engine uses time of day, day of the year, day of the week, outdoor-air dry-bulb temperature, and relative humidity (or dew point) as independent variables. The WBE module is currently being extended (as part of another task under the same project – Task 2.6) to support the use of up to five independent variables selected by an expert user, such as plug loads, occupancy loads, meals served, etc., to model the end-uses.

The WBE module uses a daily energy consumption index (ECI) to show deviations in the actual energy consumption from the expected energy consumption. The expected energy consumption is estimated based on the baseline model that is automatically developed with historical energy consumption. The daily energy consumption index (ECI) for 1 day is calculated as follows:

$$ECI = \frac{\sum_{h=0}^{23} Actual_h}{\sum_{h=0}^{23} Predicted_h}$$

where ECI is the energy consumption index, $Actual_k$ is the actual consumption for the k^{th} hour, and $Predicted_k$ is the predicted consumption for the k^{th} hour.

If the actual energy consumption and the estimated expected energy consumption are the same, by definition, the ECI equals 1.0. As the actual energy consumption deviates from the expected, the ECI values also deviate from 1.0. In general, ECI values between 0.9 and 1.0 are considered good. However, because of measurement errors and the inability to measure all the independent variables that strongly influence energy consumption, ECI values between 0.8 and 1.2 are thought to be reasonable[4]. The sensitivity of fault detection (or detection of abnormal operation) can be adjusted to provide more or fewer faults depending on the user preference.

7.1 Basic Description of the WBE User Interface

The user interface for the WBE tool displays the energy consumption index (ECI) as a time-series of daily results for major end-use categories, as shown in Figure 89. There are three primary end-uses (thermal energy, chiller (or packaged unit) electric, and HVAC electric) and

[4] The WBE actually uses a statistical measure that depends on the size of the deviation as well as how well that energy consumption is known for those conditions (related to the variance of the historical data) and only alerts the user when the deviations about 1.0 are statistically significant.

two derived end-uses (total building electric and total building energy)[5]. The total building electric includes the chiller, HVAC, lights, and equipment electric consumption.

After the data are processed, the WBE diagnostician alerts the building operator when the difference between the actual and expected end-use consumption is statistically significant, i.e., if the ECI values are significantly greater than or less than 1.0. When the deviation is statistically significant, the WBE alerts the operator with an enlarged red square as shown in **Figure 90**. Unlike the OAE diagnostician, the WBE diagnostician does not provide a list of potential causes for abnormal consumption, although it does estimate the cost of the energy impact just like the OAE diagnostician (Figure 91). Like the OAE, the WBE diagnostician also has five levels of sensitivity that control sensitivity of detection and false alarms.

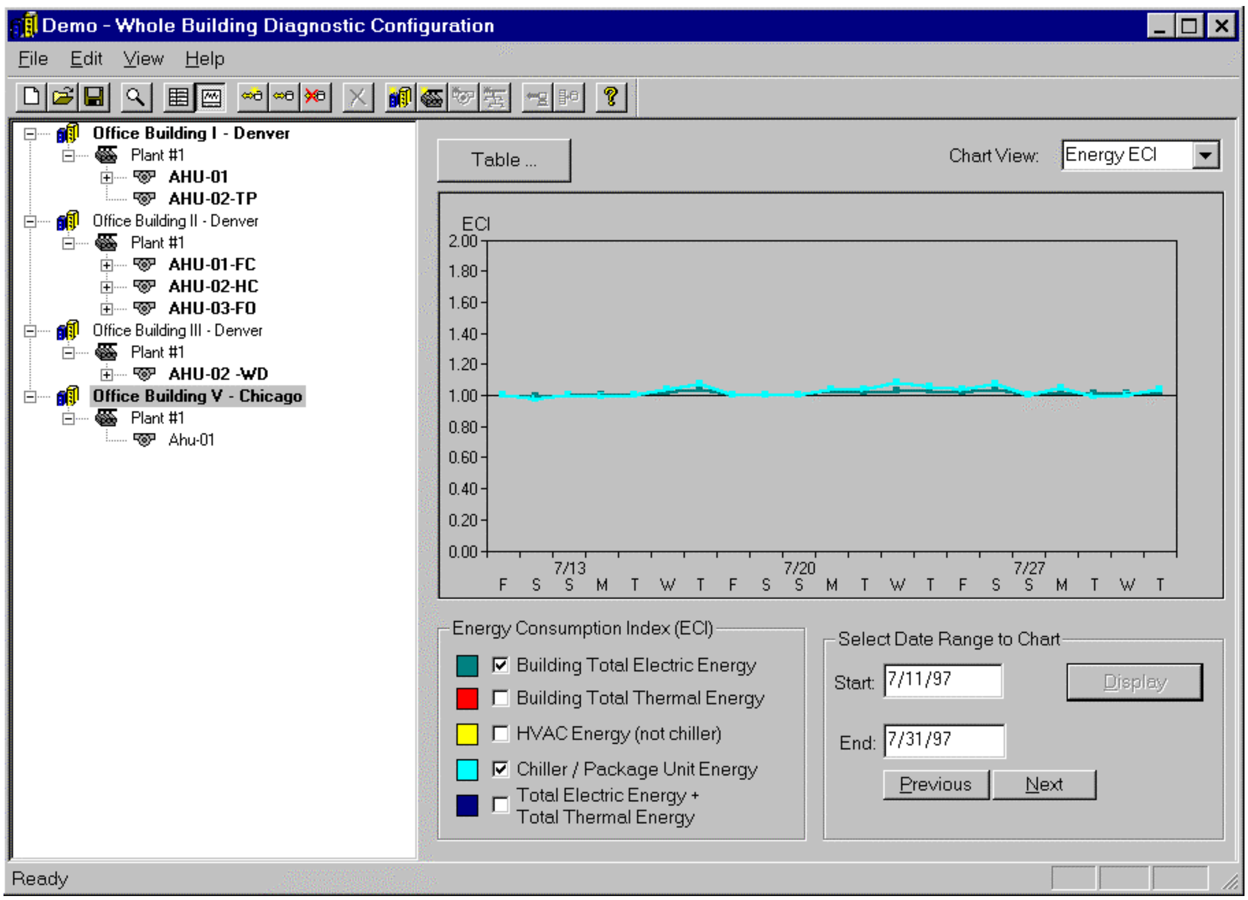
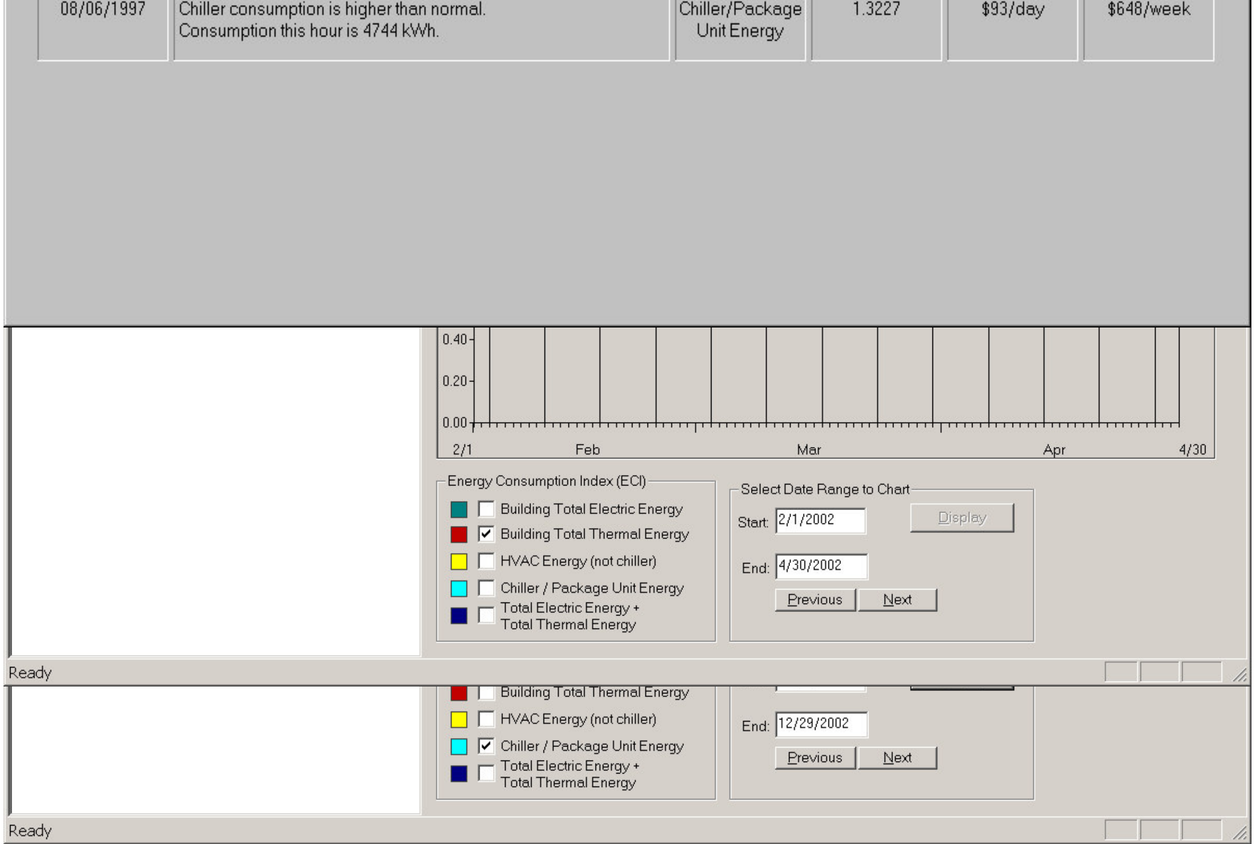
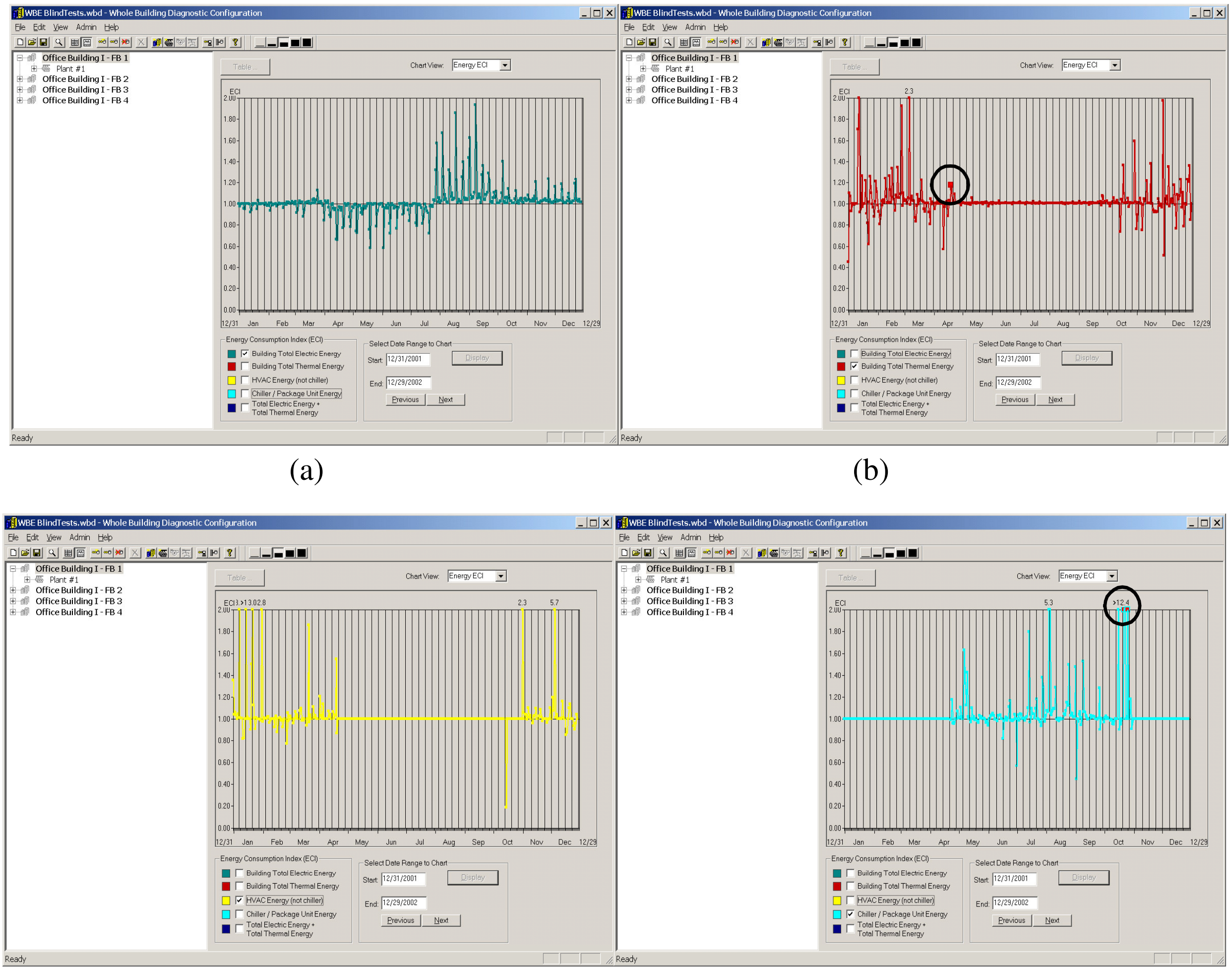


Figure 89 – WBE Screen Shot Showing ECI Values in the Normal Range

[5] The WBE is being enhanced as part of another California Energy Commission PIER project. These enhancements will allow users to select both dependent and independent variables of their choice.


08/06/1997
Chiller consumption is higher than normal.
Consumption this hour is 4744 kWh.
Chiller/Package Unit Energy
1.3227
$93/day
$648/week
0.40
0.20
0.00
2/1
Feb
Mar
Apr
4/30
Energy Consumption Index (ECI)
Building Total Electric Energy
Building Total Thermal Energy
HVAC Energy (not chiller)
Chiller / Package Unit Energy
Total Electric Energy +
Total Thermal Energy
Select Date Range to Chart
Start: 2/1/2002
Display
End: 4/30/2002
Previous
Next
Ready
Building Total Thermal Energy
HVAC Energy (not chiller)
Chiller / Package Unit Energy
Total Electric Energy +
Total Thermal Energy
End: 12/29/2002
Previous
Next
Ready



(a) (b)

(c) (d)

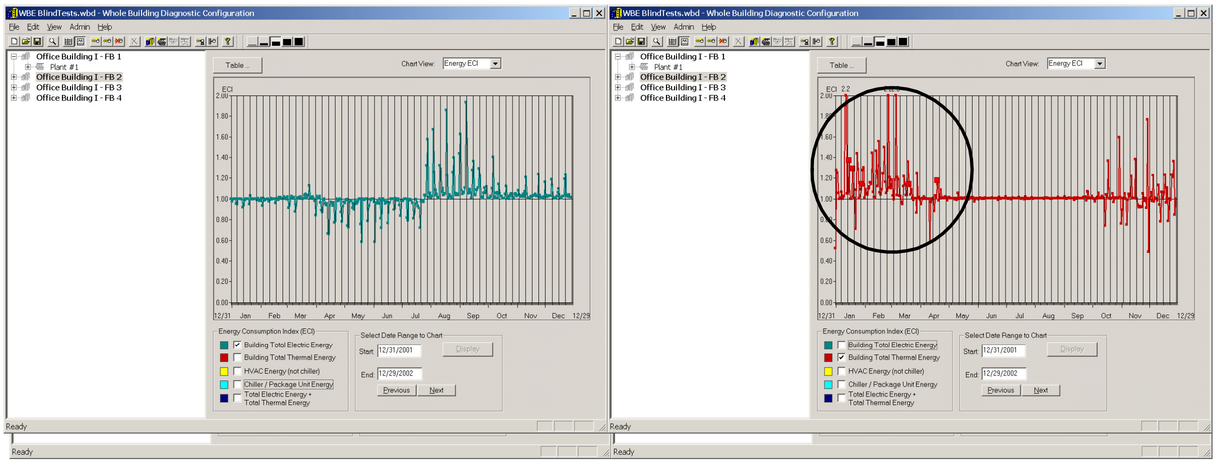
Figure 102 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity and (d) Chiller Electricity for the WBE-FB1 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)

7.5.2 Data Set WBE-FB2

The data set WBE-FB2 represents the second of the four blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and boiler energy consumption. The WBE diagnostic results for WBE-FB2 are shown in Figure 103. Although there are several days where ECI values are significantly different from 1.0 for total electricity use and thermal energy consumption, the WBE identified problems with thermal energy consumption and 2 days for chiller electricity consumption (marked by circles in sub-figures (b) and (d)). Because the deviation in chiller energy consumption did not persist for a prolonged period, it is considered normal operation by the WBE. However, the WBE identified several days as having problems for thermal energy consumption, as shown in Figure 104. It appears that the actual thermal energy consumption is significantly different from expected for several days between January 14 and April 20, 2002. An ECI problem detail for one of the problem days is shown in Figure 105.

WBE Result: The data for all end-uses with the exception of the thermal energy end-use for blind-test WBE-FB2 represent normal building operation. Thermal energy end-use shows an increase in consumption for January 14 through April 20, 2002.

(a) (b)



(c) (d)

Figure 103 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity and (d) Chiller Electricity for the WBE-FB2 Fault Data set with Normal Sensitivity (December 31, 2001, through December 29, 2002)

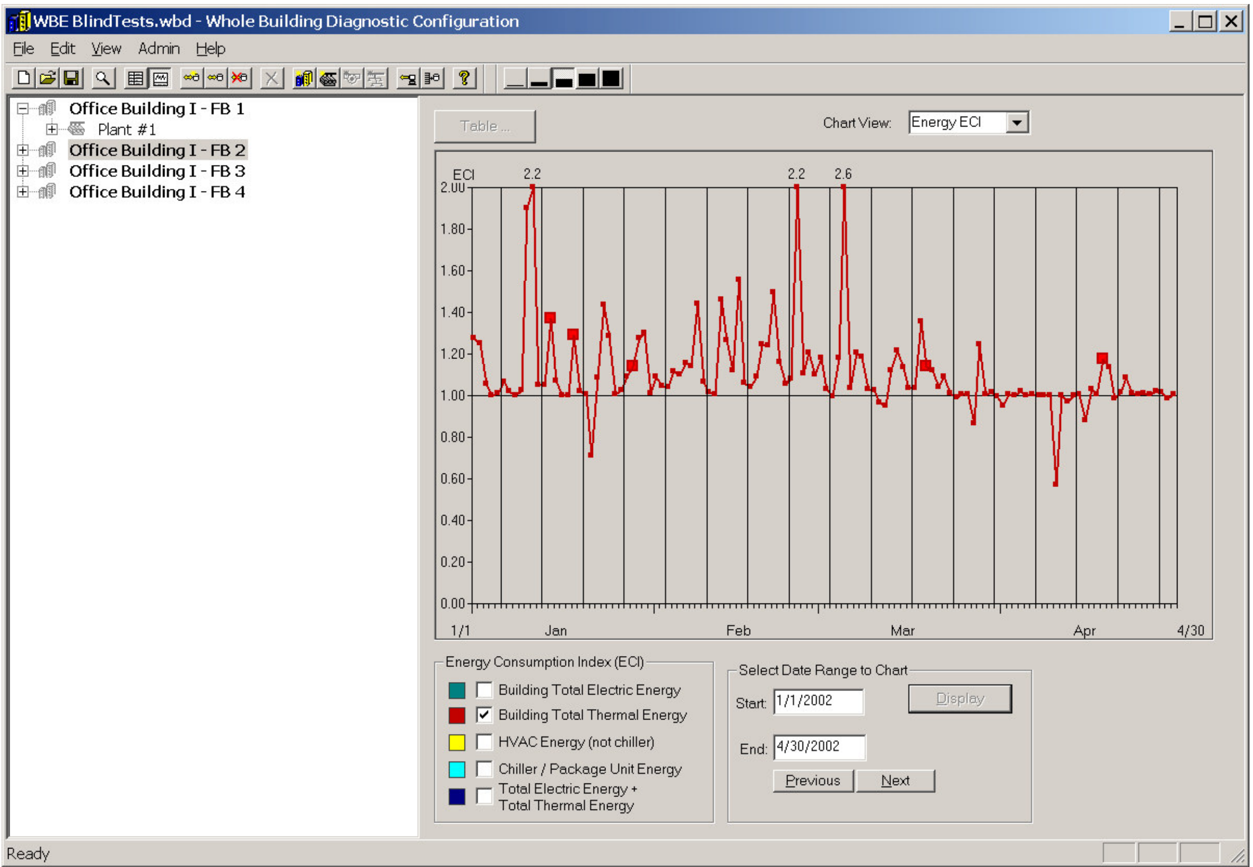
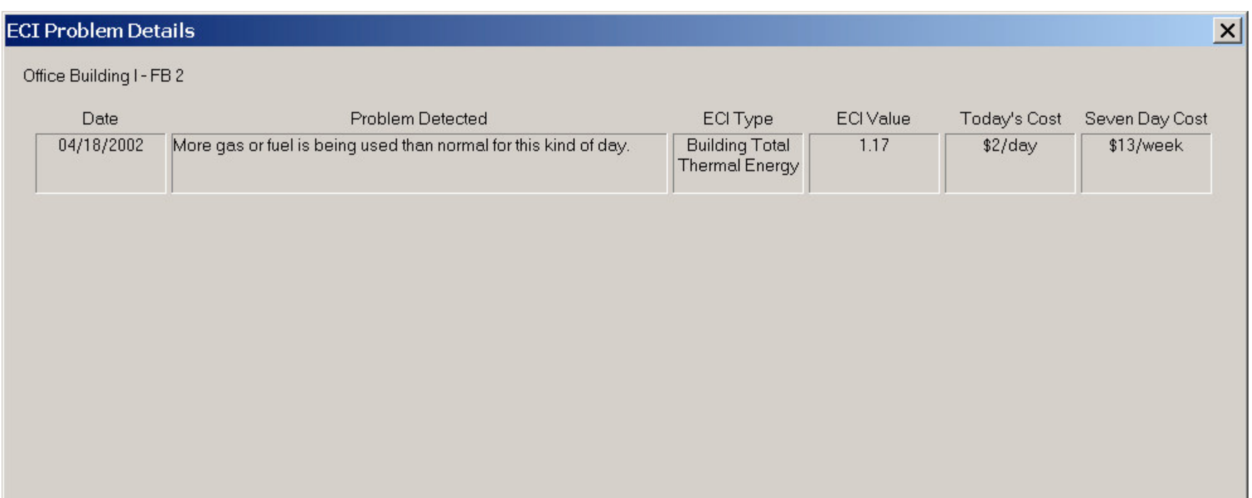


Figure 104 – WBE Diagnostic Results for Thermal Energy Consumption for the WBE-FB2 Fault Data Set with Normal Sensitivity (January 1 through April 30, 2002)


ECI Problem Details

Office Building I - FB 2

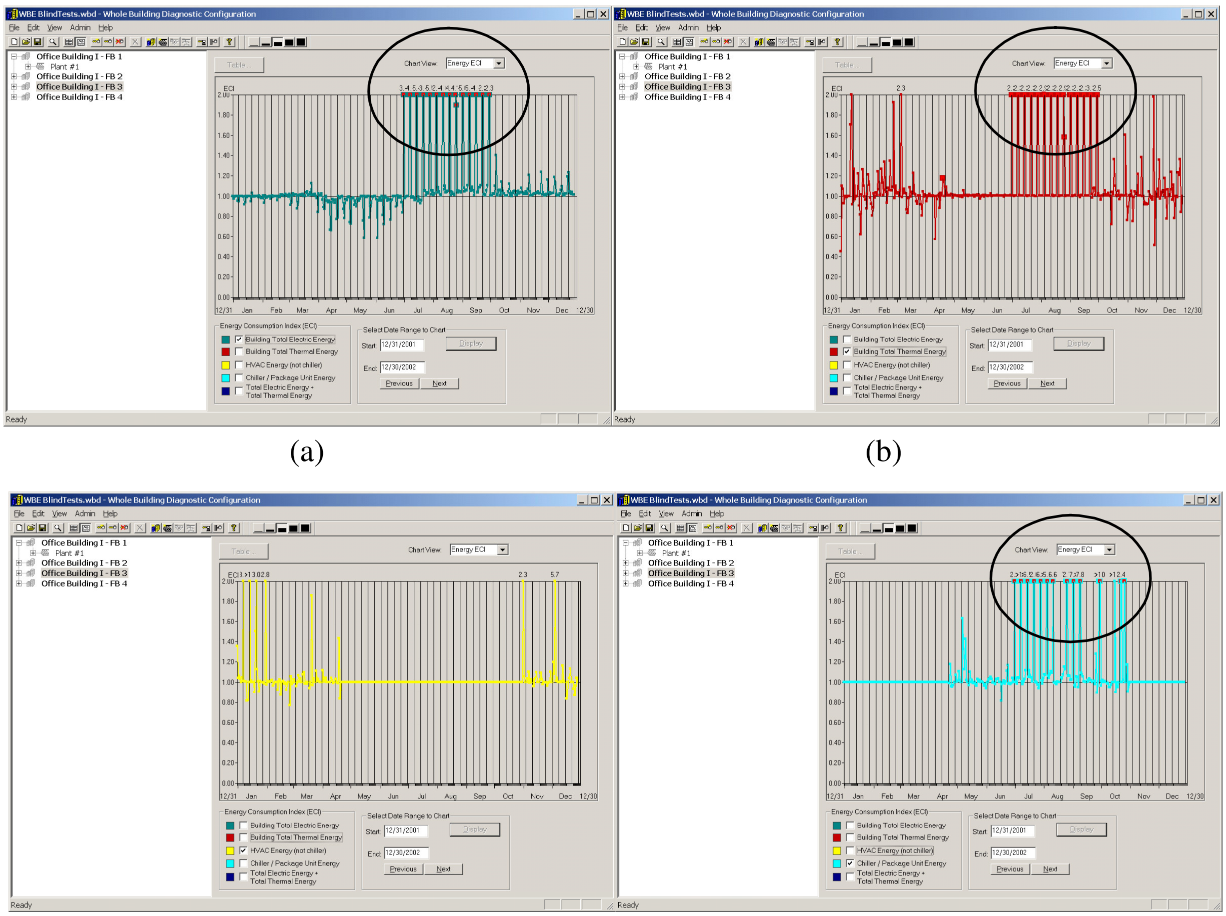
Date	Problem Detected	ECI Type	ECI Value	Today's Cost	Seven Day Cost
04/18/2002	More gas or fuel is being used than normal for this kind of day.	Building Total Thermal Energy	1.17	$2/day	$13/week

Figure 105 – ECI Problem Details from the WBE Module for April 18, 2002

7.5.3 Data Set WBE-FB3

The data set WBE-FB3 represents the third of the four blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and boiler energy consumption. The WBE diagnostic results for WBE-FB3 are shown in Figure 106. The WBE has identified an increase in consumption for all end-uses with the exception of HVAC electricity (marked by ellipses in sub-figures (a), (b) and (d)). More detailed screen shots of individual end-uses are shown in Figure 107, Figure 108, and Figure 109. The increase in consumption for all three end-uses occurs only on weekends and spans the same time period (June 30 through September 30, 2002). Because the increase in the total electric energy consumption (Figure 107) and chiller electric energy consumption (Figure 109) coincide, the problem is probably related to the chiller electricity use.

WBE Result: Data for all end-uses with the exception of the HVAC electric energy end-use for blind test WBE-FB3 represent abnormal building operation during weekends for the time period spanning June 30 through September 30, 2002.



(a) (b)

(c) (d)

Figure 106 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity and (d) Chiller Electricity for the WBE-FB3 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)

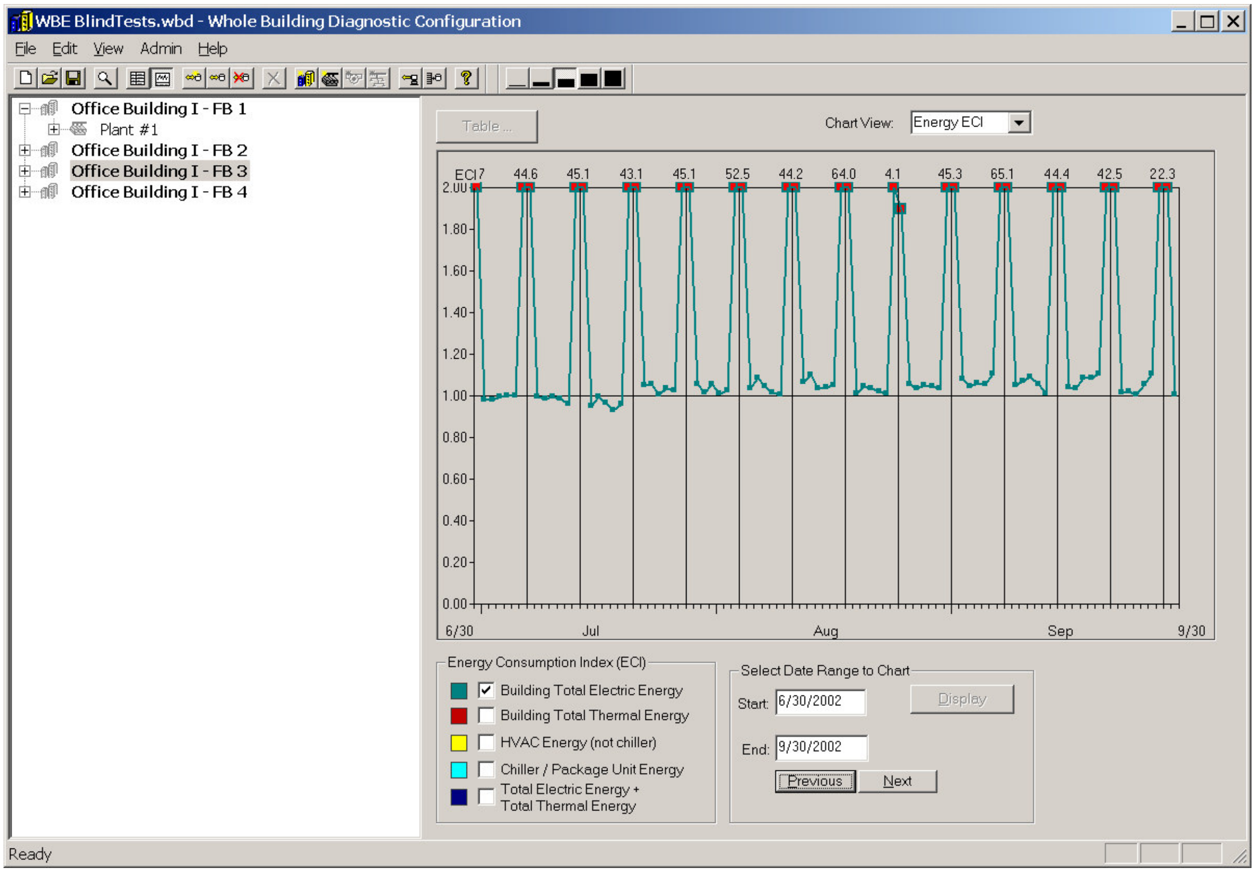


Figure 107 – WBE Diagnostic Results for Total Electricity Consumption for the WBE-FB3 Fault Data Set with Normal Sensitivity (June 30 through September 30, 2002)

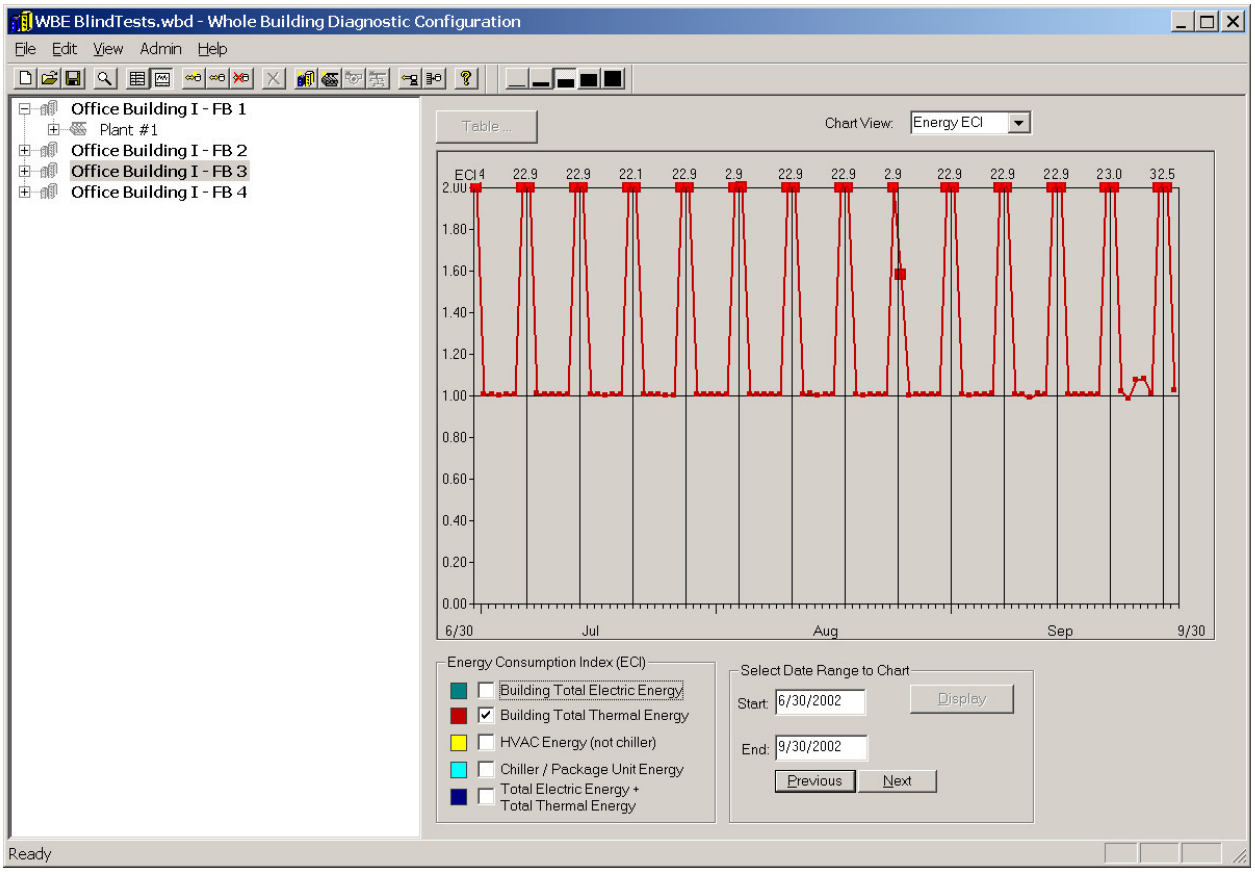


Figure 108 – WBE Diagnostic Results for Thermal Energy Consumption for the WBE-FB3 Fault Data Set with Normal Sensitivity (June 30 through September 30, 2002)

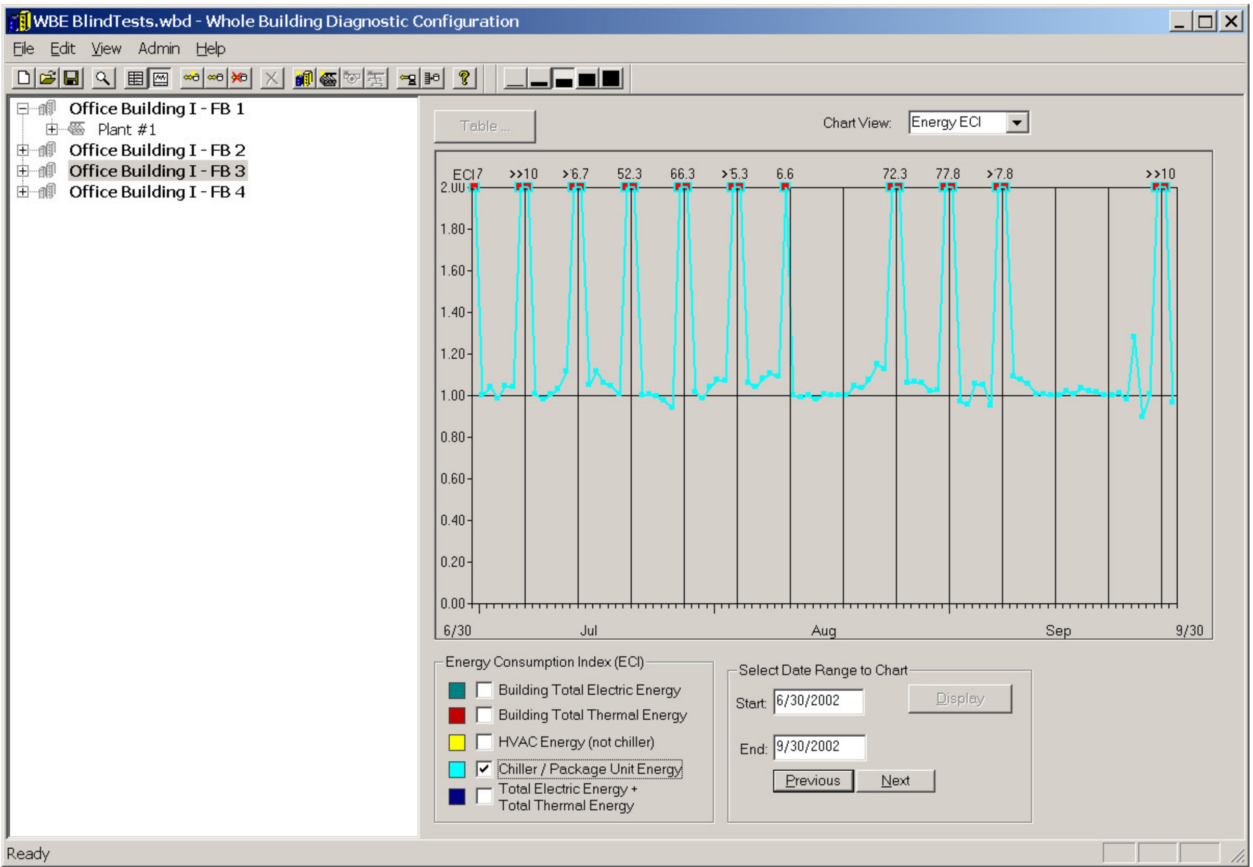
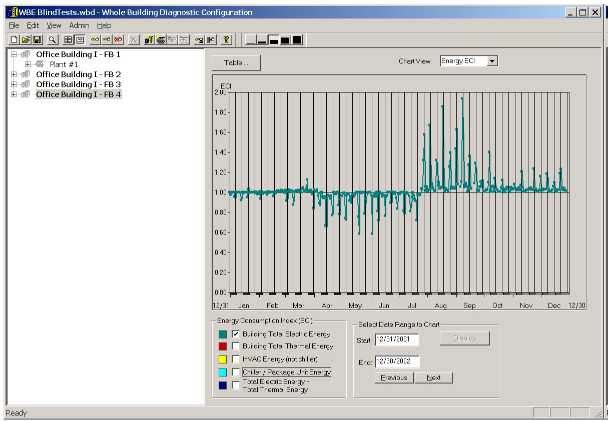


Figure 109 – WBE Diagnostic Results for Chiller Electricity Consumption for the WBE-FB3 Fault Data Set with Normal Sensitivity (June 30 through September 30, 2002)

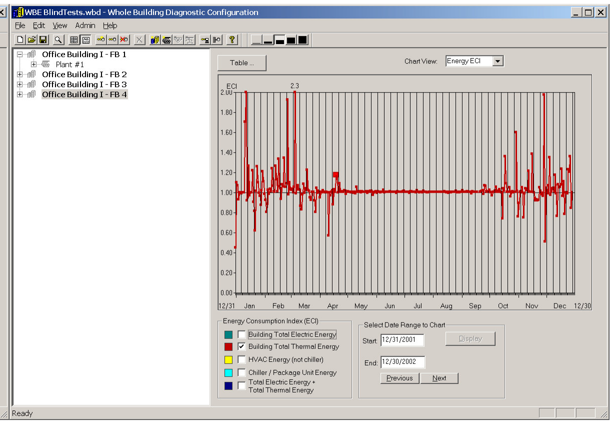
7.5.4 Data Set WBE-FB4

The data Set WBE-FB4 represents the last of the blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and boiler energy consumption. The WBE diagnostic results for WBE-FB4 are shown in Figure 110. The WBE has identified an increase in consumption for chiller electricity consumption (marked by circles in sub-figure (d)). A more detailed screen shot of the affected time span is shown in Figure 111. The increase in chiller electric energy consumption spans from August 1 through September 30, 2002. Although it is not from a 2-month view of the results, closer examination reveals that the chiller consumption may be increasing gradually over a time period spanning from the middle of June through the end of September, 2002 (Figure 110).

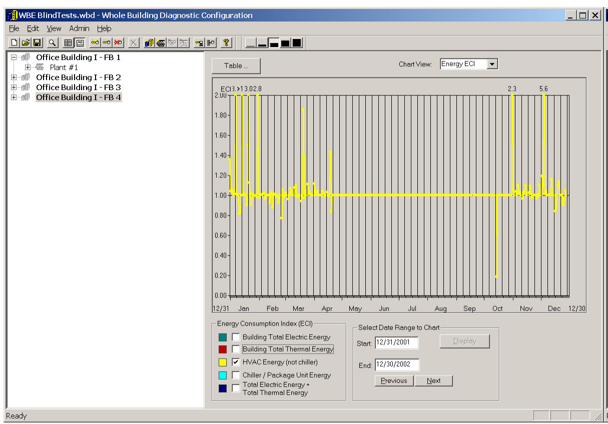
WBE Result: Data for all end-uses with the exception of the chiller electricity use for the blind test WBE-FB4 represents normal building operation. The chiller electricity consumption appears to be gradually increasing from June through September 2002, although the WBE only identified problems for the time span of August through September 2002.



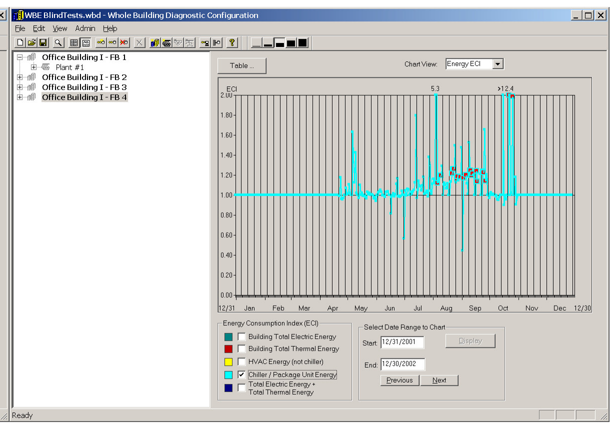
(a)



(b)



(c)



(d)

Figure 110 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity, and (d) Chiller Electricity for the WBE-FB4 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)

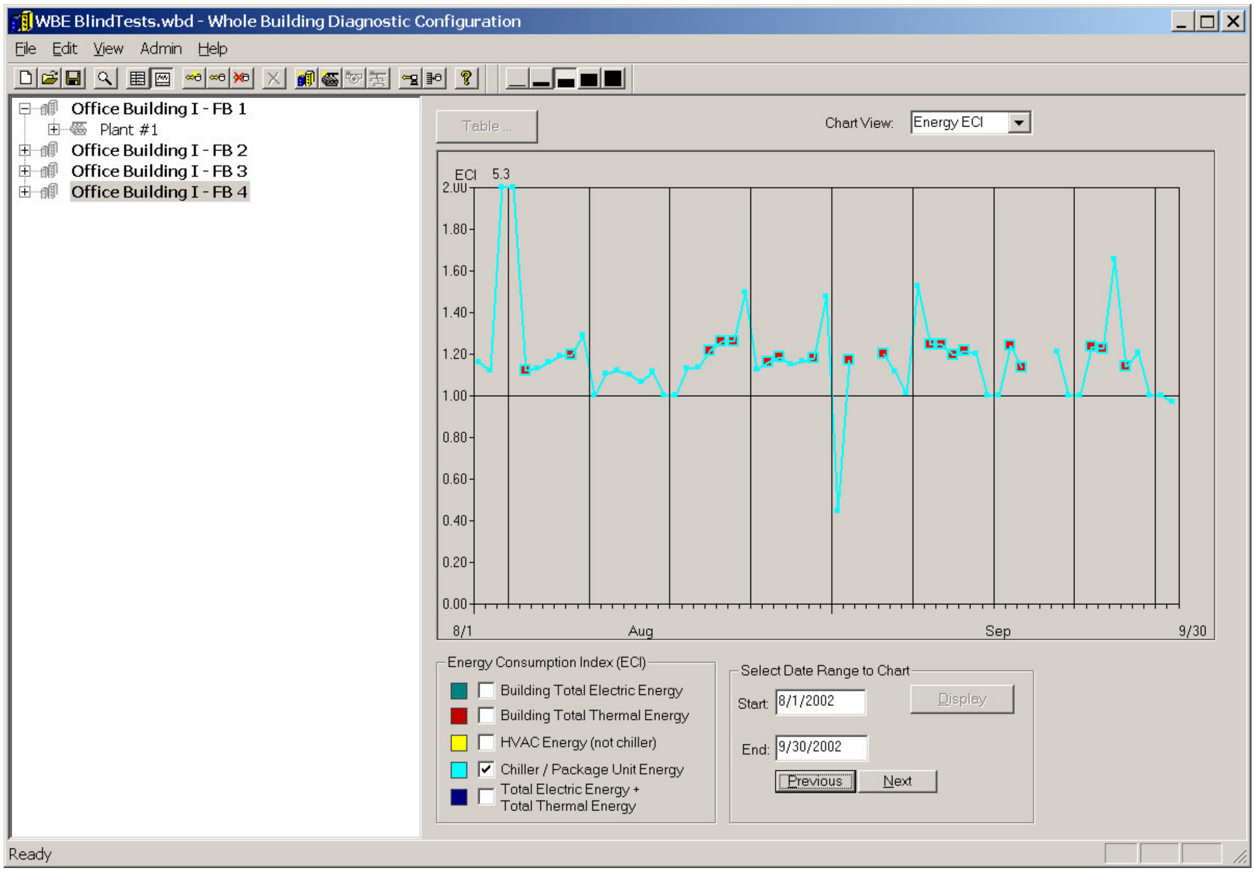


Figure 111 – WBE Diagnostic Results for Chiller Electricity Consumption for the WBE-FB4 Fault Data Set with Normal Sensitivity (August 1 through September 30, 2002)

8 Summary of Blind Test Results

In this section the results from the OAE and the WBE diagnostic modules are compared with the actual faults instigated in the VCBT environment.

8.1 Comparison of Faults Identified by the OAE with Actual Faults

Faults detected and diagnosed by the OAE diagnostician and the actual faults instigated in the VCBT environment are compared in Table 14. The blind test is identified by number in the first column of the table; the second column lists the major fault categories that were identified by the OAE for each blind test. The categories that were more frequently identified are listed first. There are three major fault categories: 1) inadequate or low ventilation (blue), 2) energy waste (red) and 3) other problem (controls, sensors, simultaneous heating and cooling). In general, the most frequently identified fault category represents the actual fault. Although there are only three major fault categories, there are a number of faults that fall into each of the three categories.

The OAE also provides a detailed description of each fault. Depending on the type of fault and method of instigation, a fault can manifest in different categories based on the prevailing conditions, as is the case for some of the blind tests.

The fourth column in Table 14 lists the possible causes that the OAE reports. Because the list gets refined and changes over time, the most commonly listed causes are provided in Table 14. The order of the list is significant because the most likely cause will rise to the top if the fault continues for a significant amount of time. Column five shows the actual fault instigated in the VCBT environment (or the cause of the fault). Column six provides the overall result of the test by indicating whether the findings of the WBE are correct, false positive, false negative, or inconclusive. Comments are provided in the last column of the table.

Although in Section 6.5 most of the results were based on normal sensitivity with few at high, it did not include any discussion of results with low sensitivity setting. For comparison the results of all three settings (low, normal and high) are summarized in Table 14. The shaded row for each test identifies the conclusion from analysis of blind test data.

Table 14 – Comparison of the Results from the OAE Diagnostician with Actual Faults.

Test	Sensitivity Setting	OAE Diagnostician: Detection – Fault Categories[6]	OAE Diagnostician: Diagnosis – List of Possible Causes[7]	Actual Fault Instigated (VCBT Simulation)	Test Result	Comments
Z1-SS-F5A	Low	1. Energy waste - Not fully economizing.	1. Maximum Outdoor-Air Fraction (OAF) is set too high in the OAE configuration. 2. Damper System fails to fully open in economizer mode. 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 5. Supply-air set point incorrectly set too low. 6. O/A damper stuck between minimum[8] and fully closed position.	Recirculation air damper leakage	Correct	

[6] Fault categories have been ordered by frequency of occurrence. In cases where the OAE could not identify any faulty operation, none of the categories identified is highlighted.
[7] The highlighted item is the most likely of the list of possibilities presented to the user; the selection is based on user discrimination of the results.
[8] Minimum position refers to the required minimum to meet the minimum ventilation requirements during occupied hours when mechanical cooling or heating is operating.

	Normal	**1. Energy waste - Not fully economizing.**	1. Maximum Outdoor-Air Fraction (OAF) is set too high in the OAE configuration. **2. Damper System fails to fully open in economizer mode.** 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.	Recirculation air damper leakage	Correct	
	High	1. Energy waste - Not fully economizing.	1. Maximum Outdoor-Air Fraction (OAF) is set too high in the OAE configuration. 2. Damper System fails to fully open in economizer mode. 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.	Recirculation air damper leakage	Correct	
Z2-SS-F5B	Low	1. Normal Operation		Normal operation	Correct	
	Normal	1. Normal Operation		Normal operation	Correct	

	High	1. **Inadequate ventilation - during occupied hours while NOT economizing.** 2. Energy waste. 3. Other Problem.	1. Error in entering ventilation schedule. 2. **O/A (outdoor-air) damper system is too closed during occupied hours when the economizer is off.** 3. **O/A damper stuck between minimum and fully closed position.** 4. Supply-air flow increased without a proportional increase in outdoor-air intake. 5. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 6. Temperature sensor problem.	Normal operation	Correct	At normal sensitivity OAE indicated normal operation; however, when the sensitivity was increased OAE reported that the damper position was correctly positioned but the OAF was too low.
Z3-SS-F5C	Low	1. Normal Operation		Return-Air temperature sensor drift	False negative	
	Normal	1. Normal Operation		Return-Air temperature sensor drift	False negative	
	High	1. Other problem - temperature sensor problem. 2. Energy waste. 3. Inadequate ventilation – during occupied hours while NOT economizing.	1. O/A damper system is stuck between fully open and minimum position. 2. Supply-air set point incorrectly set too low. 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.	Return air temperature sensor drift	False negative	The drift in the return-air temperature sensor was not detectable because of the choice of the outdoor conditions for the test. Refer to the report for more details.

Z1-HS-F4	Low	1. Normal operation.		Supply-air temperature sensor drift	False negative	
	Normal	1. Normal operation.		Supply-air temperature sensor drift	False negative	
	High	**1. Energy waste.**	1. Maximum OAF is set too high in the OAE configuration. **2. Supply-air set point incorrectly set too low.** 3. O/A damper system fails to fully open in full economizer mode. 4. Supply-air flow increased without a proportional increase in outdoor-air intake. 5. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 6. O/A damper stuck between fully open and minimum position.	Supply-air temperature sensor drift	False negative	

Z2-HS-F4	Low	1. Normal operation.		Normal Operation	Correct	
	Normal	1. Normal operation.		Normal Operation	Correct	
	High	1. Normal operation.		Normal Operation	Correct	
Z3-HS-F4	Low	**1. Other problem - temperature sensor problem.**	**1. Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Mixed-air temperature sensor failure	Correct	
	Normal	**1. Other problem - temperature sensor problem.**	**2. Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Mixed-air temperature sensor failure	Correct	
	High	1. Other problem - temperature sensor problem.	3. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Mixed-air temperature sensor failure	Correct	
Z1-SS-F6	Low	**1. Other Problem - temperature sensor problem.** 2. Energy waste. 3. Inadequate ventilation – during occupied hours while NOT economizing.	**1. Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Outdoor-air temperature sensor failure	Correct	
	Normal	**1. Other Problem - temperature sensor problem.** 2. Energy waste. 3. Inadequate ventilation – during occupied hours while NOT economizing.	**1. Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Outdoor-air temperature sensor failure	Correct	

	High	**1. Other Problem - temperature sensor problem.** 2. Energy waste. 3. Inadequate ventilation – during occupied hours while NOT economizing.	**1. Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Outdoor-air temperature sensor failure	Correct	
Z2-SS-F6	Low	1. Normal Operation.		Return-air temperature sensor drift	False negative	
	Normal	**1. Other problem - temperature sensor problem** 2. Energy waste 3. Inadequate ventilation – during occupied hours while NOT economizing.	1. **Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Return-air temperature sensor drift	False negative	
	High	1. Other problem - temperature sensor problem 2. Energy waste 3. Inadequate ventilation – during occupied hours while NOT economizing.	1. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Return-air temperature sensor drift	False negative	
Z3-SS-F6	Low	1. Normal Operation		Outdoor-air damper stuck at minimum position	False negative	

	Normal	**1. Energy waste – low economizer flow.**	1. Maximum OAF is set too high in the OAE configuration. **2. O/A damper system fails to fully open in full economizer mode.** 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 5. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Outdoor-air damper stuck at minimum position	Correct	
	High	1. Energy waste – low economizer flow.	1. Maximum OAF is set too high in the OAE configuration. 2. O/A damper system fails to fully open in full economizer mode. 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 5. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Outdoor-air damper stuck at minimum position	Correct	
Z1-SS-F8	Low	1. Other problem - temperature sensor problem.	1. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Mixed-air temperature sensor drift	Correct	

	Normal	1. **Other problem - temperature sensor problem.**	1. **Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Mixed-air temperature sensor drift	Correct	
	High	1. Other problem - temperature sensor problem.	1. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Mixed-air temperature sensor drift	Correct	
Z2-SS-F8	Low	1. Normal operation.		Normal operation	Correct	
	Normal	1. Normal Operation.		Normal operation	Correct	
	High	**1. Inadequate ventilation – during occupied hours while NOT economizing.** 2. Other Problem - temperature sensor problem. 3. Energy waste.	1. Error in entering ventilation schedule. **2. O/A damper system is too closed during occupied hours when the economizer is off.** 3. Supply-air flow increased without a proportional increase in outdoor-air intake. 4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 5. **O/A damper stuck between minimum and fully closed position.** 6. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Normal operation	False Positive	At normal sensitivity OAE indicated normal operation; however, when the sensitivity was increased OAE reported that the damper position was correctly positioned but the OAF was too low.
Z3-SS-F8	Low	1. Normal operation.		Recirculation-air damper leakage	False negative	

	Normal	1. **Energy waste - not fully economizing.**	1. Supply-air flow increased without a proportional increase in outdoor-air intake. 2. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 3. Temperature sensor problem. 4. Maximum OAF is set too high in the OAE configuration. 5. **Damper system fails to fully open in economizer mode.**	Recirculation-air damper leakage	Correct	
	High	1. Energy waste - not fully economizing.	1. Supply-air flow increased without a proportional increase in outdoor-air intake. 2. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 3. Temperature sensor problem. 4. Maximum OAF is set too high in the OAE configuration. 5. Damper system fails to fully open in economizer mode.	Recirculation-air damper leakage	Correct	
Z1-CS-F9	Low	1. Incomplete diagnosis.		Supply-air temperature sensor failure	False negative	
	Normal	1. Normal operation.		Supply-air temperature sensor failure	False negative	

	High	**1. Inadequate ventilation – during occupied hours while NOT economizing.**	1. Error in entering ventilation schedule. **O/A damper system is too closed during occupied hours when the economizer is off.** 2. Supply-air flow increased without a proportional increase in outdoor-air intake. 3. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. 4. **O/A damper stuck between minimum and fully closed position.** 5. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Supply-air temperature sensor failure	Correct	

Z2-CS-F9	Low	1. Energy waste – excess outdoor-air.	1. OAE is set up for temperature based economizer, but the actual control may be based on enthalpy. 2. OAE is set up with differential economizer controls, but the actual controls may be based on high limit. 3. O/A ventilation controller failed in open state. 4. Economizer controller failed in open condition **5.** O/A damper system is stuck between fully open and minimum position. 6. O/A damper is stuck in fully open position. 7. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Economizer control logic fault	Correct	

Normal	**1. Energy waste – excess outdoor-air.**	1. OAE is set up for temperature based economizer, but the actual control may be based on enthalpy. 2. OAE is set up with differential economizer controls, but the actual controls may be based on high limit. **3. O/A ventilation controller failed in open state.** **4. Economizer controller failed in open condition** **5. O/A damper system is stuck between fully open and minimum position.** 6. **O/A damper is stuck in fully open position.** 7. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Economizer control logic fault	Correct	

	High	1. Energy waste – excess outdoor-air.	1. OAE is set up for temperature based economizer, but the actual control may be based on enthalpy. 2. OAE is set up with differential economizer controls, but the actual controls may be based on high limit. 3. O/A ventilation controller failed in open state. 4. Economizer controller failed in open condition 5. O/A damper system is stuck between fully open and minimum position. 6. O/A damper is stuck in fully open position. 7. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Economizer control logic fault	Correct	
Z3-CS-F9	Low	1. Incomplete diagnosis.		Return-air temperature sensor drift	False negative	
	Normal	**1. Other problem - temperature sensor problem.**	**1. Mixed-, return- and/or outdoor-air temperature sensor has failed.**	Return-air temperature sensor drift	Correct	
	High	1. Other problem - temperature sensor problem.	1. Mixed-, return- and/or outdoor-air temperature sensor has failed.	Return-air temperature sensor drift	Correct	

8.2 Comparison of Faults Identified by WBE with Actual Faults

The results from the tests of the WBE diagnostician are summarized in Table 15. Each blind test is identified by number in the first column of the table; the second column indicates whether or not there was an abnormal condition detected in the data set, and the end-use with the abnormal condition is identified as well. Unlike the OAE diagnostician, the WBE only identifies abnormal conditions but does not provide a list of possible causes of the abnormal condition. By resolving total building energy consumption into major energy use categories, it does, however, enable the user to identify the end use responsible for abnormal energy consumption detected at the whole-building level. Column three shows the actual fault that was simulated, and column four provides the overall result of the test by indicating whether the findings of the WBE are correct, false positive, false negative, or inconclusive. Comments are provided in the last column of the table.

Table 15 – Comparison of the Results from the WBE Diagnostician with Actual Faults

Test	WBE Diagnostic Results	Actual Fault Instigated in Simulations	Test Result	Comments
WBE-FB1	Normal	WBE23: 10 % increase in HVAC electrical consumption (April 1 – June 30, 2002)	False Negative	Because the magnitude of HVAC consumption is low (15 kWh/day); at 10% change doesn't result in a cost impact i.e., greater than $10/day; therefore, WBE (as designed) didn't detect this fault

Test	WBE Diagnostic Results	Actual Fault Instigated in Simulations	Test Result	Comments
WBE-FB2	Higher than normal thermal energy consumption from January 14 through April 30, 2002	WBE35: 15 % increase in boiler gas consumption (1 January 1 - March 31, 2002)	Correct	There was a statistically significant increase in thermal energy consumption only for a few days; generally, this is not considered a problem, but because the ECI values were greater than 1 and also given the problem with training, this end-use, it is identified as a problem.
WBE-FB3	Higher than normal thermal and chiller energy consumption during weekends June 30 through September 30, 2002, for thermal energy consumption and June 30 through September 30, 2002, for chiller energy consumption	WBE09: Scheduling problem – same internal loads weekdays and weekends (July 1 through September 30, 2002)	Correct	
WBE-FB4	Higher than normal chiller energy consumption August 1 through September 30, 2002	WBE22: Progressively developing increase in chiller electrical energy consumption (electricity consumption increases linearly from 0 % to 25 % increase) (July 1 through September 30, 2002)	Correct	Because the fault was progressive, WBE didn't detect it until the fault was significant (after August 1, 2002)

9 Summary and Recommendations

In addition to generating several data sets representing normal operations and know faults, 15 blind data sets for testing the capabilities of the OAE diagnostician and 4 blind data sets for testing the WBE diagnostician were generated. Data sets for the OAE were generated using the VCBT emulation environment, and data sets for the WBE were generated using just the HVACSIM$^+$ simulation environment. The VCBT emulation and the simulation for the WBE data were successful in generating data representing normal and faulty operations.

9.1 Outdoor-Air Economizer Diagnostician

Of the 15 data sets for the OAE, 12 data sets represented “faulty” AHU operation and 3 data sets represented normal operation. The OAE was successful in detecting faulty operation with 10 of the 12 “faulty” data sets. In addition to detecting the faults, the OAE diagnostician also provides a list of possible causes for the fault. Because diagnosing the cause of the actual fault with limited sensor information is difficult, the OAE provides a list of potential causes rather than a single cause. In most cases, the list of potential causes contained the actual cause of the fault. The OAE was successful in detecting and diagnosing a variety of mechanical and control faults including stuck and leaking dampers, sensor drift, sensor failure, and control logic and sequencing errors.

The OAE was unsuccessful in detecting the faults in two data sets because the conditions were not favorable for detection of the fault, i.e., the fault did not have a significant adverse impact on either the ventilation requirement or the energy consumption. If the fault conditions persisted beyond the three-week period and data were available, conditions would have become more favorable for detection of these faults as the weather changed and the OAE would have then detected them.

The OAE successfully identified all three normal data sets as being fault free with a normal sensitivity setting. However, when the sensitivity of detection was increased, the OAE reported that two data sets that were labeled fault free by NIST had lower than expected outdoor-air fractions (OAFs) for a number of hours. A sample message from the OAE is shown in Figure 113; it states that although the outdoor-air damper position was correct, the outdoor-air fraction computed from the measured values of the outdoor-, mixed- and return-air temperatures was significantly lower than expected. Examination of the three-week trend of the OAF revealed that the average OAF during the three-week period was less than 6% when the expected value was 15%.

In general, the OAF is somewhat uncertain because it is estimated as the ratio of two temperature differences, which are often small because the temperatures are close to one another. When they are small, for example, during the swing season (spring and fall), the OAF has a potential for even taking negative values because of uncertainty in temperature measurements. Figure 112 shows the distribution of OAF for one test when the conditions were not favorable for economizing. When the outdoor conditions are not favorable for economizing, the expected OAF should be around 0.15 for this test. However, as seen from Figure 112, the OAF is negative for over half the time and significantly biased (i.e., thirty two of the values are below 15% while only 5 are above 15%). Although we expect the calculated OAF to be uncertain, ordinarily data from the field will not have this degree of bias around the expected value (see Figure 112); it will be more symmetric about the expected value, unless a fault is present. Because the OAF was less than the expected value for many hours, the OAE reported faulty operation when the sensitivity setting was set to high. Additional field tests may be required to understand this phenomenon better and its effects on fault detection.

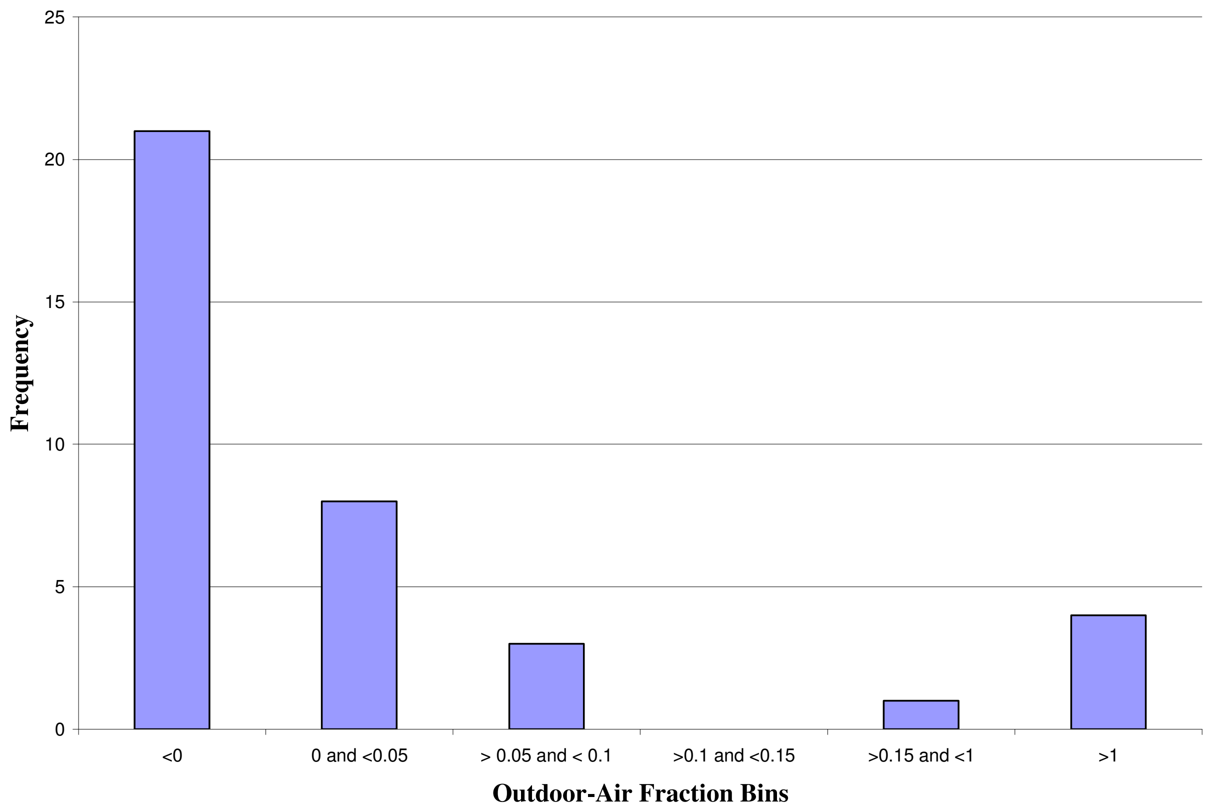


Figure 112 – Distribution of Outdoor-Air Fraction for Conditions When it is not Favorable for Economizing (i.e. expected Outdoor-Air Fraction is 0.15)

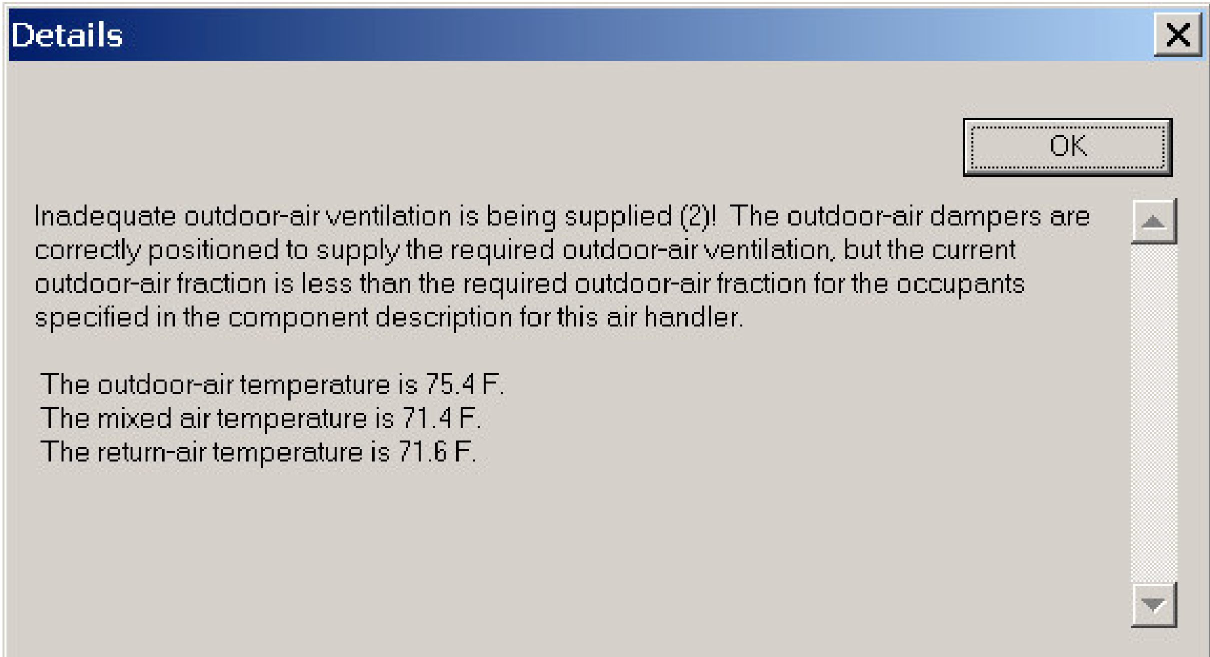


Figure 113 – Screen Shot Showing Details Message for F5B-SS-Z2

9.2 Whole-Building Energy Module

NIST generated four blind data sets to test the capabilities of the WBE diagnostician. The WBE successfully identified faults for three of the data sets. The fourth data set was created for a 10% increase in HVAC electric energy consumption for a 2-month period. The WBE did not identify the fault for this end-use because the magnitude of the difference between expected and actual consumptions was low and the corresponding cost impact was small. The WBE has a threshold for energy cost impact of $10/day, i.e., if the energy cost impact does not exceed $10/day, the WBE does not report a fault. In this case, the energy cost impact was less than $1/day and, therefore, no fault was reported.

9.3 Recommendations

As reported earlier, diagnosing the cause of the fault with limited sensor data is difficult because of lack of physical redundancy. In addition, proper selection of sensitivity settings for both OAE and WBE modules is critical in balancing fault detection sensitivity against the rate of false alarms. Additional laboratory and field tests are required to establish more definitive guidelines for users, but even then, the selection of sensitivity settings will depend on the preferences of the users.

Three specific recommendations from this study include:

- Develop analytical techniques to improve isolation of the causes of faults without additional sensors
- Study impact of sensitivity settings further
- Develop guidance for operators for selecting sensitivity settings.

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